

# Enabling technologies, transitions, and industrial systems in technology foresight: Insights from advanced materials FTA

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### ARTICLE INFO

*Keywords:*

Future-oriented technology analysis (FTA)  
Innovation systems  
Technologies  
Lifecycle  
Industrial systems

### ABSTRACT

This paper investigates opportunities to enhance Future-oriented Technology Analysis (FTA) of emerging technologies within innovation systems. We address key challenges faced by policy makers developing innovation strategies for emerging technologies. In particular, we explore ways FTA might be structured to investigate the complex innovation system journeys of novel technologies as they are developed, diffuse, and get deployed. In doing this, we draw on concepts from technology and operations management and related literatures to more carefully characterise: (1) 'infrastructural technologies' required to develop emerging technologies; (2) key technology transitions involved in diffusion; and (3) complex industrial value networks into which they may eventually get deployed.

We investigate the extent to which these categories are already used within national technology foresight exercises. In particular, we review over 240 international FTA-related policy, strategy, and analysis documents for 'advanced materials'. We conclude that – although generally used inconsistently and unsystematically within FTA – these categories repeatedly emerge as important elements in many final foresight reports and strategies. We conclude by arguing that these categories should be carefully considered in initial FTA design. And that, by doing so, FTA exercises may better reveal potential 'innovation system failures' and help policy makers coordinate policy actions in response.

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## 1 Introduction

This paper explores opportunities to enhance Future-oriented Technology Analysis (FTA) for key emerging technologies within innovation systems. We investigate potential ways that FTA might be more effectively structured to analyse the complex innovation journeys of novel science-based technologies, as they are developed, diffuse, and get deployed in evolving industrial and market contexts. In particular, we focus on the role of FTA in supporting innovation system policy-making and the development of

national strategies for key emerging technologies (or related initiatives). In this context, we pay particular attention to introducing new dimensions of analysis which may have the potential to reveal important categories of 'innovation system failure', where there may be a role for government.

Key enabling technologies have the potential to enhance national competitiveness in high value industries, as well as contribute to solutions to important socio-economic challenges in a range of areas from healthcare to climate change.

Given the importance of such technologies, many national governments have significant initiatives to support and promote the strategic development of key emerging technologies. Recent initiatives include the UK's '*Great Technologies*', the technology priority programmes of the German '*New High Tech Strategy*', activities related to the priority 'Manufacturing Technology Areas' of the US '*National Advanced Manufacturing Strategy*', and European Union programmes related to '*Key Enabling Technologies*' (KETs).

These initiatives typically involve a range of policy measures (often delivered by a range of ministries and innovation agencies), including public investment in R&D, as well support for education and workforce development, the development of regulatory frameworks, support for standardisation, knowledge dissemination and network building, and – where appropriate – activities to ensure public assurance.

Many of the most important of these emerging technologies are, however, embedded in increasingly complex application systems, produced by ever more complex manufacturing systems, involving increasingly interdependent and complex value chain and supply chain systems, and are being deployed in (potentially unforeseen) ways with uncertain impacts (Dosi, 1988; Rosenberg, 1996).

In this context, there is increasing awareness of the multiplicity and variety of 'innovation system failures' (or weaknesses) that can block a promising emerging technology's complex emergence – its extended journey from early laboratory demonstration through multiple

technology lifecycles and diffusion into ever larger and more mature markets.

Given the complexity of emerging technology innovation journeys, range of potential future outcomes and impacts, and possible 'failures' that can block their development, government policy design needs structure to navigate this complexity and anticipate possible 'failures'. Many governments have established foresight programmes and, in some cases specialist units, which have developed capabilities to provide forward-looking analysis for the policy process (Yasunaga et al., 2009; Miles, 2005; Georghiou, 1996; see Georghiou et al. (eds), 2008 for a comprehensive review of various countries). More recently there has been a push to embed foresight in specific policy development activities (Weber et al., 2012), including the development of national innovation strategies for key emerging technologies. The capabilities being developed include the use of Future-oriented technology analyses<sup>1</sup> (FTA) – a set of tried and tested future-oriented frameworks and methodologies that can be used to underpin policy design processes.

Formal FTA can be an important informant for government technology strategy<sup>2</sup>, policy, and programme development (Cagnin and Keenan, 2008). These analyses help to explore key barriers and enablers of future impact, and the ways current and potential future actors and activities might influence future technological outcomes (and have societal impact). These insights can be of significant value in defining programme objectives and prioritising opportunities and challenges.

<sup>1</sup> FTA was a term developed to establish a community around similar efforts in technology foresight, technology assessment, and technology forecasting (Cagnin and Keenan, 2008; Porter et al., 2004; Scapolo and Cahill, 2004) and arguably includes technology roadmapping and technology intelligence (Porter, 2010; Radar and Porter, 2008).

<sup>2</sup> The strategy development exercises can occur ahead of programme implementation (e.g. a composite strategy exercise preceded the establishment of the UK's National Composite Centre, see BIS, 2009) or as part of the programme (NSTC, 2014, e.g. 2011a) – the development of a strategy can even be the core objective of the programme (Featherston and O'Sullivan, 2015).

FTA has proven a valuable tool for informing a range of science, technology, and innovation (STI) policy domains; however, key innovation system trends are making it harder to understand the evermore complex innovation journeys of key emerging technologies. As stated above, many important emerging technology-based applications becoming more complex and knowledge-intensive and being produced by more complex manufacturing systems. Furthermore, the accelerating pace of technological innovation and increasing global competition mean that there is greater urgency to accelerate national development, diffusion, and deployment of new technologies. In particular, there is an imperative to both gain competitive advantage by bringing these technologies to market first, but also, in many cases, to capture value through scale-up and high value manufacturing within the national economy.

In this context, FTA exercises have been incorporating a number of concepts related to innovation systems to help account for these developments (see Andersen and Andersen, 2014; Cagnin et al., 2012, and also refer to the call for papers for this special issue). Their inclusion have enhanced FTA, in particular by highlighting the importance of innovation system structure (distinguishing clearly between different types of actor), articulating broad innovation system functions (distinguishing between the potential roles of those actors), and highlighting the potential for innovation 'system failures' (potential barriers to the effective development, diffusion, and use of new knowledge).

The increasing technological and manufacturing complexity, the pace of technical change, and growing competition challenge us to explore barriers to the innovation of emerging technologies in more detail. Are there further innovation system distinctions that should be

made? Are there additional structural elements within innovation systems, which are potential sources of innovation system failure, and which merit more direct attention within FTA?

In this paper, therefore, we explore the potential for some new FTA dimensions of analysis. In particular, we investigate the potential importance of key structural elements related to the innovation journeys of novel technologies as they are developed, diffuse, and get deployed. In doing this, we draw on concepts from technology and operations management and related literatures to more carefully characterise: (1) 'infrastructural technologies' which may be required to *develop* emerging technologies; (2) key phases of emergence lifecycles, as technologies *diffuse* into new application domains and ever larger, more mature markets; and (3) key stages of industrial value chains into which the technologies may get *deployed* (and where economic value may be captured).

More detailed FTA insights into these categories have the potential to significantly enhance policy making for emerging technology innovation. Government interests in STI policy include funding technologies with (quasi-)public good natures (Link and Scott, 2013, 2011; Tassey, 2003), accelerating innovation (Sainsbury, 2007), and capturing value nationally (Berger, 2013; Cabinet Office, 1993; Sainsbury, 2007). These have led to practical concerns in government with managing technology portfolios and infrastructure (Government of Japan, 2016; HLG KET, 2015; PCAST, 2012), coordinating various government actors (HLG KET, 2014; House of Commons, 2010; US Committee on Science, 1998), and understanding the impact on real industrial structures (BMBF, 2014; HLG KET, 2015).

In the following section (section 2.0), we explore the recent evolution of FTA - how it has drawn on

innovation systems concepts to date and how it motivates a deeper look into the nature (and structural elements) of innovation. In particular, this paper draws on categories and dimensions and structures provided by other academic literatures – in particular the economics of emerging technologies and innovation, technology management, and operations management. In sections 3.0 to 5.0, we explore the potential of these categories to more systematically structure FTA exercises for key emerging technologies.

In section 6.0, we investigate the extent to which these categories are already used within national technology foresight exercises. In particular, we review over 200 international foresight-related analyses and strategy documents for '*advanced materials*'. The findings from the literature and the review of advanced materials strategies (and related foresight) are then discussed (section 7.0). In particular, we observe that although generally used inconsistently and unsystematically within FTA – many of the proposed categories repeatedly emerge as important elements in many final foresight reports and strategies.

We conclude by arguing that these categories should be carefully considered in initial FTA design. And that, by doing so, FTA exercises may better reveal potential 'innovation system failures' and help policy makers coordinate policy actions in response.

## **2 FTA, technology foresight, and innovation systems**

Innovation system foresight has been offered as the most recent generation of technology foresight, and adopts concepts from the innovation systems literature to reflect recent developments in our understanding of innovation (Andersen and Andersen, 2014). This 'generation' of foresight, and FTA, is drawing on

a number of useful concepts from the innovation systems literature to understand the nature of the systems that generate novel technologies and technological innovations. Innovation systems has provided guidance on the structure of these systems, such as the breakdown of its structure into actors, linkages, and institutions (see Edquist, 2005) and concepts that help to define how innovation systems function (see Bergek et al., 2010; Hekkert et al., 2007; Johnson, 2001). These insights have been applied to technology foresight and innovation policy (Alkemade et al., 2007; e.g. Bergek et al., 2008).

The innovation systems literature has also supplemented the market failure argument for government intervention with innovation 'system failures' or weaknesses (see Klein Woolthuis et al., 2005; Smith, 2000); together these help explore the role government policy might take in enabling and accelerating innovation. Frameworks have been developed that use these understandings of 'system-based' functions, structure, and categories of market and system failure to help guide STI policy development (e.g. Wiecek and Hekkert, 2012). These concepts have and will continue to further enhance the FTA that underpin these policy efforts (see the rest of this special issue). However, there is general concern that innovation systems theory is difficult to operationalise (Chaminade and Edquist, 2010; Markard et al., 2015).

Policy developers and advisors recognise the need to understand the innovation system from which novel technologies emerge. The US government, for example, used an understanding of the innovation system to identify actions that would lead to strengthening system performance, which led to the introduction of the National Manufacturing Innovation Institutes (NMIIs) that aim to provide the 'national infrastructure for supporting the translation

activities for bridging fundamental research and manufacturing' (PCAST, 2012, p. 21). The European Commission's KET programme also pays attention to the effective functioning of the innovation system and is built on the notion that effective management is central to producing innovation (HLG KET, 2015). The system that generates innovation has been of increasing concern to policymakers because studies have made strong cases for the relationship between innovation and national competitiveness (Nelson and Winter, 1982), and because novel technologies are seen as central to dealing with global 'grand' challenges, such as climate change, and generate rapid improvements to public services, such as healthcare (Government of Japan, 2016; RCUK, 2007).

It has long been argued that there is a role for governments in supporting R&D in emerging technologies because of their potential returns and attributes that deter private investment (Arrow, 1962; Nelson, 1959). Interest in concepts from innovation systems, from a public policy perspective, has been to help scrutinise national innovation capacity and linkages (system structure), understand knowledge development, diffusion, and use (innovation system functions) and reveal innovation rate-limiters and blockages (market and system failures). However, an initial review of emerging technology programmes, strategies, and evidence documents (BMBF, 2004; CSTP, 2010; e.g., EPSRC, 2013; HLG KET, 2011; PCAST, 2012) suggested that governments pay attention to particular aspects of innovation and technology that challenges us to look further into technology infrastructure, emergence dynamics, and the industrial systems into which novel innovations are deployed to help structure and enhance the conceptual frameworks used to support STI policy development.

The next three sections focus on these governments concerns by drawing on concepts of

the role of different technology types to help advance technology development; technology lifecycles to understand emergence dynamics; and industrial system elements and configurations to help explore possible absorptive capacity of national industrial systems. Useful concepts related to these innovation system challenges, and that help address the aforementioned policymaker concerns (funding technologies with (quasi-)public good natures, accelerating innovation, and capturing value nationally), were found in the literature on the economics of innovation, technology management, and operations management respectively.

### **3 Developing and advancing technical knowledge: technology types and innovation infrastructure**

Innovation systems theory acknowledges that technologies do not emerge in isolation. They emerge in a network of actors, whose interactions are defined by institutions (Edquist, 1997) and who are endowed with, and support by, innovation infrastructure (Galli and Teubal, 1997; Van de Ven, 1993), of which infrastructure technologies are a part (Tasse, 2007, 2005, 1991).

Governments support the development of the technical knowledge underpinning innovation, but do not want to displace private investment with public funding. Governments have for some time funded fundamental science (for an account of government support see Bush, 1945) and economics has since provided an underpinning theoretical justification for this support. In short, fundamental science has risk, uncertainty, and economies of scope (Arrow, 1962; Nelson, 1959); spillovers and appropriability issues (Arrow, 1962; Nelson, 1959); long timeframes to returns (Nelson, 1959); technological complexity (Tasse, 2007); and imbalances between private and

social rates of return (Nelson, 1959) such that it does not tend to attract private investment. These attributes, particularly spillovers and appropriability, mean that fundamental science is (at least in part) a *public good*. Tassey (2005) argues that infrastructure technologies *can* have some of these attributes, making them variably public, quasi-public, or private goods.

Acknowledging these deterrents to private investment, governments pay attention to investing in a number of different technology categories to support and enable R&D. Along with support for fundamental science, governments provide research infrastructure (a form of infrastructural technologies) through research councils and Science Foundations (e.g., Research UK, the US National Science Foundations), and other support facilities (such as the UK's National Physics Laboratory). They also help coordinate research infrastructure through strategies and roadmaps (ESFRI, 2011, 2009, RCUK, 2012, e.g., 2010). This begins to reflect the portfolio of technologies that government support that contribute to innovation.

Useful categories and theoretical constructs that can be integrated into FTA to help structure and consider technology infrastructure and its role in innovation. Tassey (Tassey, 2007, 2005, p. 92) identifies a number of categories of technological knowledge, including the science base, generic technologies, proprietary technologies, and infrastructure technologies (hereon *infratechnologies*), based on their contribution to innovation. Inspired by this categorisation of technology, production technologies have been added because they often enable the deployment of a technical innovation.

The *science base* refers to the fundamental research where scientific phenomena are discovered and explored and technological possibilities

are conceived. Much of the work done in the science base is done in publicly funded research institutions, such as universities, and research intensive firms. Research that adds to the base science includes work done in mathematics, physics, chemistry, life-sciences, and engineering.

*Generic technologies* (or application platform technologies) are technologies that have become platforms which can be built upon and configured, possibly with other technologies, to form a number of sequential generations of proprietary application technologies. Tassey (2007, p. 110) refers to this as the point where the technology has been demonstrated ('proof of concept'). The public good content of the technology begins to fall when the product goes through phases of prototyping and demonstration, and private ownership of the resulting application configurations start to be identified or assigned.

A *proprietary technology* is a technology that has reached a point of specificity in configuration and application where intellectual property rights (e.g., technical or design patents, industrial design rights, or design patents) have been recognised, registered, or acquired.

Generic technologies and proprietary technologies are 'principal technologies' – technical knowledge that is advanced and combined to create commercial technologies deployed in markets. Progression on this pathway is supported by enabling technologies – Tassey's *infratechnologies* and *production technologies*. The science base contributes to both principal technologies and enabling technologies.

*Infratechnologies* are the technologies used to support the development of a principal technology and production technologies. These

include measurement and characterisation (testing) equipment, technical interfaces between technologies, analysis techniques (e.g. modelling and simulation tools and techniques), and databases. Infratechnologies are important because they enable and accelerate the development, manufacturing, and commercialisation of technologies (Tassey, 2008) and reduce technology development times (Tassey, 2007).

*Production* technologies are the tools and associated techniques that support the fabrication of a novel technology. While not part of Tassey's (Tassey, 2007, 2005) taxonomy, the capabilities of production technologies are often essential for achieving of the economic and scale attributes required to deploy technical innovations, including required levels of repeatability, cost, yield, and price-performance. Production technologies draw on the science base to understand the process of material manipulation; however processes cannot be patented (only the equipment), giving production technologies complex mix of public, quasi-public, and private good characteristics and warranting investigation as a separate category of enabling technology.

Figure 1 structures these technologies by their contribution to innovation (the result of which is a proprietary technology). This figure is adapted from Tassey (Tassey, 2007, 2005, p. 92), who applies shading to indicate the varying degrees of public good technologies in these categories have.

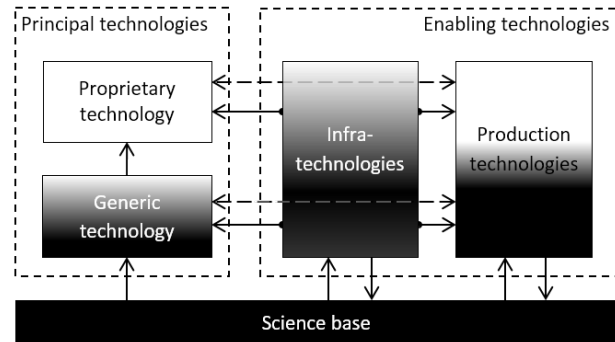


Figure 1: Characterisation of the categories of technological knowledge and varying public (dark shading), quasi-public (grey shading), and private (white) good content (Tassey, 2007, adapted from 2005, p. 92)

#### 4 Diffusing knowledge into ever larger and more mature markets: technology lifecycle emergence phases and transitions (accelerating innovation)

Diffusing knowledge for its use in industry is an important function of innovation systems (reference). Knowledge diffusion is not only important for new products, but also for enhancing existing technologies so they can be deployed into ever larger and more mature markets.

Many governments and public bodies are interested in *accelerating* the diffusion of technical knowledge, including UK government departments and agencies (Cabinet Office, 1993; e.g., RCUK, 2007), the European Commission (European Commission, 2012; e.g., HLG KET, 2015), and US agencies (e.g., NIST, 2006) and Federal government (e.g., PCAST, 2012). In the UK, for example, Innovate UK, an agency that supports further development and application of fundamental science, defines one of its main challenges as reducing the length of the innovation process and 'accelerating the journey to market' (Innovate UK, 2014, p. 6). Commercially, technological innovation it is an important route for industries to upgrade their competitive positions (Porter, 1998, p. 544). Nationally, accelerating this process helps countries catch-up and compete with high wage economies (Sainsbury, 2007). Furthermore,

accelerating technological innovation can help address the more urgent of the 'grand' societal challenges before their consequences become more severe, such as climate change and an aging population (RCUK, 2007).

Key to accelerating innovation is understanding and supporting the various phases in emergence and the transitions between the phases. Lifecycles are a concept that helps to illustrate the phases in technology development. They have been used for some time to discuss the phases, transitions, and maturity of technologies and products (Ansoff and Stewart, 1967; e.g. Gort and Klepper, 1982), corporate organisations (e.g. Miller and Friesen, 1984), and industries (e.g. Livesey, 2012; Phaal et al., 2011).

The lifecycle concept can be usefully combined with a technology roadmapping architecture

(Groenveld, 1997; Phaal et al., 2004; see, e.g., Phaal and Muller, 2009), as is proposed in the Science–Technology–Application–Market (STAM) emergence framework (Phaal et al., 2011). The STAM framework divides the industrial lifecycle into science, technology, application, and market phases and draws on demonstrators, such as commercial application demonstrators, to indicate transitions through these phases (Figure 2). The contribution of using the technology roadmapping architecture is to allow the critical innovation activities to be systematically identified and categorised and visually linked on a pathway to deployment (Phaal et al., 2010, see 2004; Phaal and Muller, 2009, p. 40). These categories of innovative activity include science, technology, system integration, product and service offering, business (models), and market (Phaal and Muller, 2009).

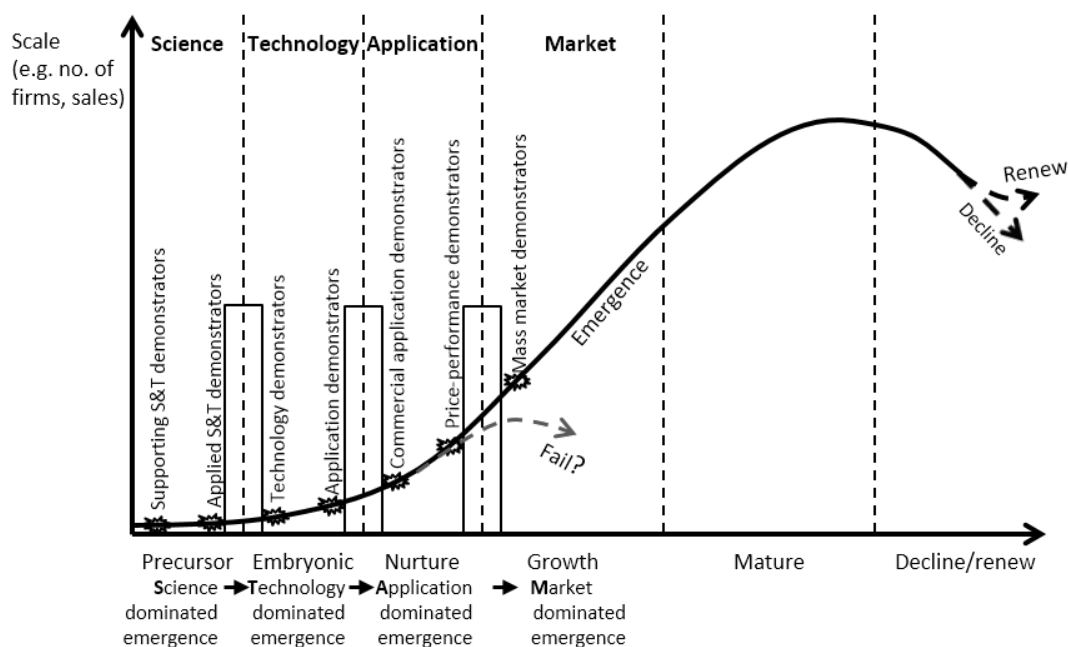


Figure 2: The STAM framework's emergence phases, transitions, demonstrators, and trajectories to new markets (adapted from Phaal et al., 2011, p. 221)

The structure provided by the STAM model could be drawn on to help explore the key transitions of technology development in FTA. The notion of

demonstrators in particular can be used as a guide for identifying where a technology is on its path to maturity and which transitions (next



demonstrators) might need attention. Furthermore, the technology roadmapping architecture provides categories of current innovative activity that could support the identification of the current 'centre of gravity' of innovative activity, potentially indicating where the key challenges and barriers are to development, where key uncertainties lie, and where government actors might play a role in supporting and accelerating further development.

## **5 Knowledge use: emergence and (re)configuration of industrial system structures**

Governments are also interested in whether the national industrial system – the parts of often global supply chains within their borders – has the ability to absorb and use knowledge being developed to ensure national value capture from their investments (and other innovative efforts). Interest in developing industrial capability to absorb knowledge and innovate has led to a number of national programmes. In the UK, for example, the Advanced Manufacturing Supply Chain Initiative (AMSCI) provided grants to UK consortia of researchers and firms within an industrial supply chain to support R&D, support closer collaboration for knowledge development and absorption, and address market failures (BIS, 2012). Further exploiting novel technical knowledge, particularly among SMEs, was also a key motivation for the introduction of the US' NMIs (PCAST, 2012). The EU's KET programme was also established to develop the technologies that underpin European supply chains, and promotes partnering researchers with actors in supply chains to ensure KET knowledge can be developed, absorbed, and used (HLG KET, 2015).

Governments are also paying attention to different groups of activities within their industrial systems for their value capture

potential. The value created and captured in production-related activities, such as design and sales, has been emphasised, particularly in advanced economies (Shih, 1996). However, manufacturing has also been acknowledged as an important source of value, both directly and indirectly, for advanced economies (e.g., Sainsbury, 2007). The US government, for example, recognised the importance of manufacturing to its national economy and the need to have domestic manufacturing to foster innovation (PCAST, 2012). This was supported by the results of MIT's Production in the Innovation Economy project, which found that domestic industries strengthened the national capacity to innovate (Berger, 2013).

The desire to understand whether the technical knowledge they are developing can be absorbed and lead to various industrial activities capturing value nationally places demands on FTA to distinguish between different elements of the industrial system and their potential geographic locations. In particular, it calls for the exploration of whether the national industrial system will exist and have the capability and willingness to absorb the technical knowledge being developed. Such information would be invaluable for STI policy development and prioritisation.

However, understanding industrial systems can be difficult because they often involve a network of actors that is made complex by the number of actors and their multiplicity of interconnections. As Tassey (2010, p. 288) puts it:

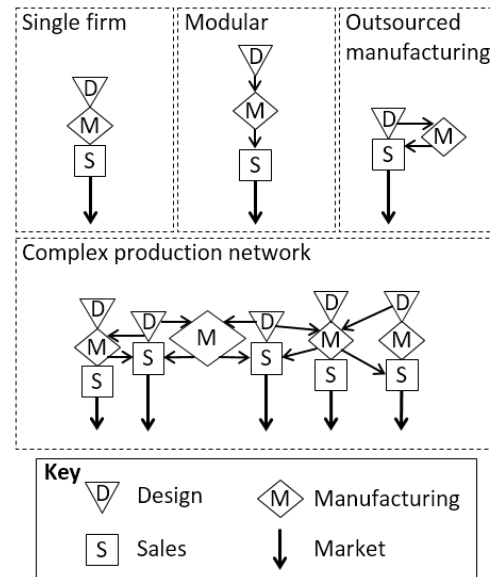
'Most modern technologies are systems, which means interdependencies exist among a set of industries that contribute advanced materials, various components, subsystems, manufacturing systems, and eventually service systems based on sets of manufactured hardware and software. The modern global economy is therefore

constructed around supply chains, whose tiers (industries) interact in complex ways.'

Furthermore, the particular configuration of supply chains has consequences for its capability and performance (Srai and Gregory, 2008).

Conceptualisations and guidance regarding the structure of the industrial system include Porter's (1998, p. 43) value system, which is a supply chain configuration of his internal (generic) value chain (Porter, 1985, p. 37); supply chains and networks (e.g., Bowersox et al., 2007; Chopra and Meindl, 2004; Christopher, 2005; Harland, 1996), production networks (Sturgeon, 2002, e.g. 2001), and value networks (Peppard and Rylander, 2006; e.g., Srai et al., 2014). This work has contributed to a number of different conceptualisations of industrial system mapping, including value stream mapping (Hines and Rich, 1997), value network configuration (Harrington and Srai, 2014; Srai et al., 2014), and organisation network (Bartlett and Ghoshal, 1989). In practice, many industrial system reference architectures have been defined, including less structured architectures (for a less-structured architecture of the EU's creative industries see Mateos-Garcia et al., 2008) to more structured views (e.g., Harrington and Srai, 2014; Srai et al., 2014).

Sturgeon's (Sturgeon, 2002, 2001) conceptualisation of the production network could be particularly useful for exploring industrial system structure in FTA exercises. This conceptualisation (depicted in Figure 3) explores different categories of activities (system elements) within the industrial system, including design, production, and sales. Furthermore, Sturgeon (2002) used these categories to explore various (re)configurations of these industrial elements, which he used to point to the potential location of these industrial and, as a consequence, points to their value capture potential.



**Figure 3: Industrial system elements, and their (re)configuration, for exploring their potential to absorb new knowledge and capture value nationally (adapted from Sturgeon, 2002)**

The market context has also been included as a category of the industrial system. Inspired by operations management's and new product development's focus on market structure, including market opportunity, alignment, and performance-price point, the consideration of market is essential to understand industrial willingness to draw on and use technical knowledge and explore possible locations of industrial activity.

The next section brings these categories together and illustrates how they were considered in a review of key international publicly-focused advanced materials policy documents.

## 6 Review of documents underpinned by FTA

### Method

To explore how government programmes, strategies, and evidence documents pay attention to different technology types, industrial system structure elements, and emergence phases and transitions, documents were reviewed and coded (scored) for the attention

they paid to the conceptual categories identified above. It reviewed publicly focused advanced materials documents from key advanced economies (the UK, USA, Germany, the EU, and Japan), which documented the results of forward looking exercises that aimed to develop technology-focused programmes, technology-focused strategies, and (future-oriented) technical 'knowledge' or intelligence. The review was used to demonstrate whether these categories emerged in their development (and therefore their underpinning exercise), whether these categories formed part of the exercise's underpinning architecture, and whether comparable documents paid different attention to the categories.

The documents were read through in-depth multiple times, reviewed and scored based on how much attention they paid to the categories. The scores were applied as follows:

- **Score 0:** not considered at all or very cursory mention
- **Score 1:** considered in passing – it was mentioned as a consideration, but little to no specifics were given
- **Score 2:** considered in some detail – broad sub-categories were used to refer generally to specific concerns or some selected specific concerns were given
- **Score 3:** considered in much detail, with specifics – breakdowns of the area were supplied; many specifics were mentioned; and economic figures or statistics (e.g., number of researchers) might have been supplied to illustrate the current state, possible future state, or both (i.e., the change)

#### *Different technology types*

The documents were scored for their attention to the different technology types identified earlier. Specifically, they were scored for their attention

to the categories in the development of advanced materials, advanced materials-based devices and components, and advanced materials-enabled products. The classification of these technologies focused on the nature and purposes that the technologies were said to have and their role in development. The categories of technology types again were:

- Base science
- Generic technology
- Proprietary technology
- Infratechnologies
- Production technologies

The generic and proprietary technology both refer to the *principal technology* being developed and distinguishing between them relied on the degree to which the technology being discussed was part of a specific product being manufactured or expected to be manufactured.

#### *Technology lifecycle phases and transitions*

In the review, each document was studied for its attention to the various phases outlined in the STAM framework (Phaal et al., 2011). These phases were indicated by the focus of the activities being supported or recommended. The phases and their correlating activities included:

- **Science** – establishing and developing the fundamental science that underpins technology or work that explores the 'supporting *scientific phenomena*' (Phaal et al., 2011, p. 221 emphasis added)
- **Technology** – the development of technical aspects of components and devices to make the product more desirable in markets. In particular, the development of their *reliability and performance*
- **Application** – development of the production and market economic aspects of a technology, including *price* and the

establishment of a larger (and more sustainable) market.

- **Market (phase)** – the maturation and *mass-application* of the technology and the products it is integrated into to the market

The transitions were more difficult to assess because they were often implicit and because development is a continual, dynamic accretion and accumulation of knowledge that makes clear transitions between phases difficult to clearly identify. Instead, the documents were reviewed based on their attention to *indicators of transition*, such as demonstrators, their emphasis on links between government programmes or government programmes linking the different areas of attention in the phases, and their articulation of minimum performance requirements that align with particular phases. The transitions were defined as (Phaal et al., 2011):

- **Science-technology transition (S-T)** – demonstration of the ‘feasibility of a scientific phenomenon’ (Phaal et al., 2011, p. 221) through applied science and technology demonstrators moving to technology demonstrators
- **Technology-application transition (T-A)** – the progression in what models ‘demonstrate’ from being niche technology application towards being applicable to wider commercial applications
- **Application-market transition (A-M)** – the movement from price-performance demonstrators to models that are designed to penetrate or generate mass market sales

#### *Industrial system structure elements*

Each document was also reviewed for its attention to various aspects of industrial system

structure into which technical developments might be deployed. It was not expected that the documents would explore specific industrial system structures or specific industrial system maps, because being so precise is beyond what the FTA exercises underpinning these documents can be expected to achieve (Abadie et al., 2010); however, documents were reviewed for their attention to general industrial configurations. The documents were scored based on their attention to the different categories of industrial activity and the main mechanism for value capture, the market (known collectively as elements of the industrial system). These were defined as:

- **Design** – the influence of novel materials on the design of new products, specifically the discussion of new product development practices and processes, and the implications of design changes on the configuration of the remaining industrial system elements
- **Manufacturing** – the production of materials; and devices, components, and (final) new product systems dependent on new materials
- **Sales** – the activities of identifying customers, establishing routes to market, and selling to customers; it also includes the consideration of aspects of functionality that assist sales
- **Market (structure)** – the specific customers and segments pursued with novel products. Sturgeon (2002) focuses on ‘lead’ firms that create, penetrate, and defend markets. In particular, the consideration of broad application spaces counted as some detail, with more extensive considerations including market breakdowns and corresponding product lines and variety and their performance. Consideration of the market also included

economic figures of market structure (in terms of value), breakdowns, and forecasts market opportunities.

*Sample selection: advanced functional materials*

Advanced materials was selected because it is important to many industrial innovations. Germany's BMBF<sup>3</sup> (2004, p. 5) reported that 'more than three quarters of [Germany's] 20 largest industrial companies classify materials research as significant to very significant for their future corporate development'. It is for its importance that advanced materials are a central focus in a number of government initiatives, including the UK's 'Great Technologies' (Willets, 2013), the German *New High Tech Strategy* (BMBF, 2010), the US 'National Advanced Manufacturing Strategy' (PCAST, 2014), and European Union's KET Initiative (HLG KET, 2011).

Advanced materials also often underpin radical novel functionality, requiring new technology infrastructure; can be deployed in multiple applications (often in different sectors), each with their own lifecycles and transition challenges; and enable the development of new product classes, which can disrupt existing industrial value and supply chains. Furthermore, these attributes of advanced materials interact to make their consideration in a public policy context quite complex. It is for these reasons it was a useful domain in which to demonstrate these categories.

The study drew on the documents studied in a review of publicly-focused advanced materials-related programme, policy, strategy, and evidence documents (see Featherston and O'Sullivan, 2014a). The 319 documents reviewed in this study dated from the year 2000 till 2014.

The documents from this review were filtered for the degree to which they focused on developing novel materials, and advanced materials-based devices, components, and products. In some instances this led to, for example, the UK's sector-based strategies for the aerospace industry, *Lifting Off* (BIS, 2013a), and the nuclear industry, *The UK's Nuclear Future* (BIS, 2013b), being included, while other sector strategies were excluded. In these cases, only content relevant to advanced materials was reviewed. This yielded 245 documents that describe government programmes; strategies; strategy development processes; FTA outputs; FTA exercises; or some mix of these. They are all forward looking and underpinned by a development *exercise* that includes an analysis of the future, whether it is implicit or explicit, and all focus on technology-enabled innovation. The sample from Japan was small (17) and biased by those documents published in English. The sample of Germany's documents (27) had similar restrictions, but some documents only in German were included. These restrictions did not apply to the UK (61), USA (67), or EU (73).

The results reflect a review of all the documents, but the 'scores' are only provided for a sample of 24 UK documents. These documents were selected to demonstrate that the categories were considered in many documents and illustrate some of their variations within a single national innovation system. Furthermore, they exemplify the breadth of authors, target audiences, document type, and target application industries within one national context (see appendix).

Figure 4 summarises the categories used in the study.

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<sup>3</sup> Federal Ministry of Education and Research (Bundesministeriums für Bildung und Forschung, BMBF)

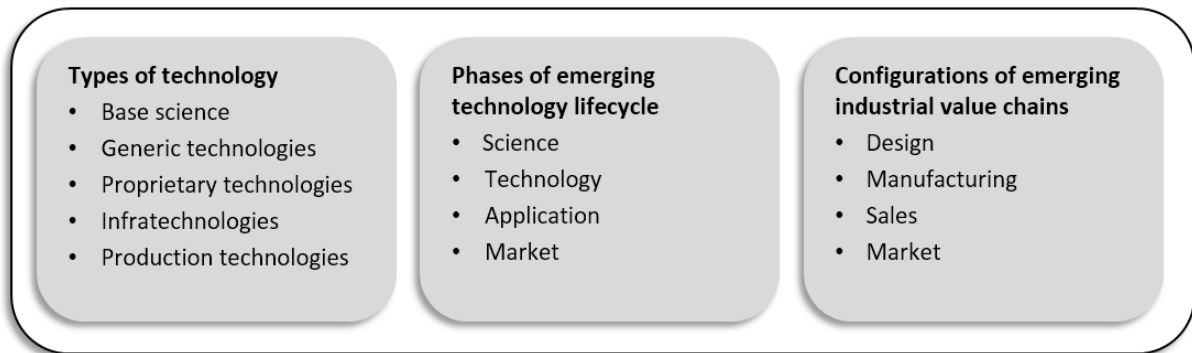


Figure 4: The categories drawn on by the framework

### Review results and observations

During the review, a number of observations were made about the roles that various organisations had in the development and publishing of the documents, the different types of organisations involved, the variety of target audiences, and the variety of application spaces to which the content of the document applied.

Each of these are likely to have had significant influence on the document and are reported in the appendices.

Table 1 summarises the attention the sample documents paid to each of the categories used as a unit of analysis in the review. Each set of categories are reported on in the following three sections.

Document	Technology types					Emergence Phases & transitions							Industrial system elements & market context			
	Base science	Generic technology	Proprietary technology	Infratechnology	Production technology	Phases				Transitions			Design	Manufacturing	Sales	Market
						Science	Technology	Application	Market	S-T	T-A	A-M				
Technology Roadmap for Composites in the Automotive Industry (NCN, 2005)	1	1	2	1	1	0	2	2	2	0	1	2	0	2	1	1
Technology Roadmap for Composites in the Aerospace Industry (NCN, 2006)	1	1	1	3	3	0	2	2	2	0	2	2	1	2	1	1
Technology Roadmap for Composites in the Construction Industry (NCN, 2006)	1	1	1	3	2	0	3	3	3	0	2	0	0	1	0	1
Technology Roadmap for Composites in the Marine Industry (NCN, 2006)	1	2	1	0	2	0	2	2	2	0	2	0	3	3	3	3
Technology Roadmap for the Metal Matrix Composites Industry (NCN, 2006)	1	2	1	1	1	0	2	3	3	0	1	2	1	1	0	0
Roadmap on Nanomaterials in Polymer Applications for the Transport Industry (IoM3, 2010)	3	2	3	2	1	0	3	3	2	0	2	1	2	2	0	1
Nanotechnology: a UK Industry View (Materials KTN & Materials UK, 2010)	1	0	2	2	2	1	1	1	2	0	2	3	0	2	1	3
Materially Better: Ensuring the UK is at the Forefront of Materials Science (EPSRC, 2013)	3	2	1	3	1	1	2	2	0	1	1	1	1	1	1	2
Engineering Grand Challenges: Report on outcomes of a retreat (EPSRC, 2014)	3	0	0	3	2	3	2	0	0	2	1	0	1	1	0	0
Key Technology Area: Advanced Materials 2008-2011 (TSB, 2008)	1	1	0	2	1	0	1	3	2	0	2	2	1	2	1	2
Nanoscale Technologies Strategy 2009-12 (TSB, 2009)	2	2	2	2	3	0	2	2	0	0	2	2	2	2	2	3
Materials R&D for Nuclear Applications: The UK's Emerging Opportunities (Sherry et al., 2010)	3	2	0	2	2	0	2	3	NA	0	3	NA	3	3	1	3
A Strategy for Materials (Materials IGT, 2006)	1	1	1	2	1	0	1	1	1	0	0	0	0	1	1	2
Functional materials (Materials UK, 2006)	3	2	0	3	2	3	3	1	0	1	0	0	0	1	0	3
Multifunctional materials (Materials UK, 2006)	2	0	0	1	1	1	1	0	0	2	1	0	0	1	0	0
Biomaterials (Materials UK, 2006)	3	2	1	2	2	3	3	1	1	0	2	0	2	2	0	2
Structural materials (Materials UK & namtec, 2006)	1	2	0	2	1	0	1	3	3	0	2	2	0	1	2	2
Structural materials - A Science and Technology Report (Materials UK, 2009)	1	2	0	2	1	0	1	3	3	0	2	2	0	1	2	2
UK Composites 2013 (Composites Leadership Forum, 2013)	1	3	0	1	1	0	2	2	1	0	2	0	1	3	2	2
The UK Composites Strategy (BIS, 2009)	0	2	2	0	2	0	2	3	3	0	2	2	1	2	2	3
Eight Great Technologies (Willets, 2013)	1	2	1	2	2	2	2	1	0	2	0	0	0	1	1	1
UK Nanotechnologies Strategy: Small Technologies, Great Opportunities (HM Government, 2010)	1	2	1	2	1	1	2	3	2	1	2	1	0	1	0	3
The UK's Nuclear Future (BIS, 2013)	0	1	2	2	2	0	1	3	NA	0	2	NA	0	2	2	3
Lifting Off (BIS, 2013)	0	1	0	2	2	1	2	3	2	0	2	2	2	3	3	1

**Table 1: The varying attention the sample documents paid to each of the categories defined for comparison (vertically)**  
**NA: not applicable**

### *Different technology types*

The reviewed documents indicated that a number of different categories of technologies

were important for the development of novel advanced materials. Of the 24 sample documents, 22 considered infratechnologies to some degree, 18 of which to a moderate or

significant degree (e.g., EPSRC, 2013; Materials UK, 2006a; NCN, 2006a); and all sample documents considered production technologies, 14 of which to a moderate or significant degree (Materials UK, 2006b; NCN, 2006a; e.g., TSB, 2009).

Innovate UK's<sup>4</sup> (TSB, 2009) *Nanoscale Technology Strategy 2009-2012* is an example of how policy documents identified a number important categories of technology. The document lists the current strengths of the UK in nanoscale technology as (TSB, 2009, p. 9, italics added):

- coatings and surfaces (*materials engineering of principal technology, drawing upon chemistry and other disciplines in the science base*).
- structural and functional materials (*science base, materials engineering of generic technology and proprietary technology*)
- modelling (*infratechnology*), design (*tools for design are infratechnologies*), and scale-up (*production*)
- [medical] controlled release, diagnostics, therapeutics (*generic technology and proprietary technology*)
- displays, memory, sensors (*generic technology and proprietary technology*)
- instrumentation for measurement (*infratechnologies*)

Particularly prevalent infratechnologies for materials included modelling and simulation, testing and characterisation, and enabling information and communication technologies. These were often drawn out because of their distinct role and importance in advanced materials R&D.

In the sample documentation, infratechnologies received considerable attention across many

documents despite, in many instances, the questions that aimed to draw out technically related information not taking account of this categories of technology explicitly. For example, *Materials Science and Engineering in Germany* (acatech, 2008) used a hypothesis, “‘gaps’ in the value chain extending from materials research and development to product manufacturing delay materials-driven innovation’ (acatech, 2008, p. 14), to explore technical gaps. Despite its breadth, this hypothesis elicited information about multi-scale simulation, incompatible data formats, and the development of strategies and roadmaps (a ‘soft’ technology). Despite broad questions similar to these gaps, infratechnologies continually emerged in the review.

The only two documents that did not pay attention to types of infratechnology were underpinned by FTA exercises that solely explored future industrial opportunities and challenges and focused on potential technical solutions rather than on the challenges that need to be overcome to develop them (BIS, 2009; NCN, 2006b). Despite this focus, it is worth noting that the NCN (2006b, appendix) identified a number of infratechnologies in a review of related documents (e.g., modelling techniques, measurement tools for the nanoscale), even if this did not find its way into the core content of the report.

Production technologies also received much attention and emerged despite not being part of the underpinning architecture. For example, *Technology Roadmap for Composites in the Aerospace Industry* (NCN, 2006a) also broadly asked participant in the workshop ‘what are the technology gaps?’ (NCN, 2006a, p. 3), which drew out the importance of technologies enabling scalability, curing, low cost autoclaving, and non-destructive testing (to name a few). Despite not

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<sup>4</sup> Formally the Technology Strategy Board (TSB)



being part of the exercise's initial architecture, this technology type continually emerged in the underpinning exercises as important contributor to, or enabler of, innovation.

Proprietary technologies were mentioned only in the context of understanding barriers to private sector adoption and deployment. This is to be expected because this review focused on documents that emphasised 'public' materials R&D, and on the development of generic materials research that provides a platform for multiple applications, rather than specific proprietary applications.

#### *Technology lifecycle: phases and transitions*

The emphasis that the documents placed on various phases and transitions of a technology lifecycle varied significantly. The transitions identified generally aligned with the phases explored with many documents paying equivalent or slightly less attention to transitions as they did the correlating phases. Notes about the indicators of transitions observed in the documents are reported in the appendix.

The results indicate that all phases of development were considered by at least some of the documents. The application phase features the most in the sample, but only marginally higher than the technology phase, and the science phase featured in the fewest documents. This suggests that most documents focused on activities that aimed to establish reliable technical performance and controlling costs, rather than focusing on understanding the fundamental scientific phenomena of the technology. This does not mean that *science* featured little in the documents. On the contrary, many of the problems identified in each phase required input from science to solve, only to decreasing degrees the closer to the market phase the problem was (e.g., BIS, 2013a).

Furthermore, the results suggest that documents 'authored' by the same organisation still aligned with the organisation's objectives, despite variations in attention to technology maturity between documents. The sector strategies, for example, which were developed by largely industry led leadership groups, generally focus on latter stages of emergence, while the EPSRC emphasised earlier emergence phases, but neither were limited to a phase or set of phases.

Some documents had a narrow focus, with only one primary focal phase (7 sample documents), while others placed emphasis on two (13 sample documents) and three (4 sample documents) phases. More significant, however, is the frequently observed decline in emphasis 'up', 'down', or both from the centre phase (or peak) of attention (see Table 1). This indicates that the underpinning exercise recognised and 'scanned' prior phases for technologies that might come into their phase of focus and where it might go, but also paid attention to the transitions from those phases, as shown in the transition data (Table 1).

Some document took a different view to transitions. Instead of identifying specific transition for a technology, they explored tools to *enable* transitions. Examples include the US' Materials Genome Initiative (NSTC, 2011b) and *Materially Better: Ensuring the UK is at the Forefront of Materials Science* (EPSRC, 2013). Other documents were very targeted on focused on very specific transitions (e.g., Sherry et al., 2010).

#### *Industrial system structure: elements and configuration*

The review revealed that several documents were conscious of the need to consider the industrial system into which advanced materials developments would be deployed. Supply chain concepts were present in a number of

documents, including Innovate UK's (TSB, 2009, p. 9) *Nanoscale Technology Strategies 2009-2012*, BMBF's (2004) *WING Programme*, acatech's<sup>5</sup> (2008) *Materials and Science Engineering in Germany*, and Lust et al.'s (2008)<sup>6</sup> *Zukunftsfeld Werkstofftechnologien*. Documents even suggest that a study of advanced materials R&D cannot be done effectively without considering the industrial systems into which it could be deployed (acatech, 2008).

However, specific attention to industrial system configurations was not reflected in many of the documents reviewed. Notable exceptions to this include *The UK Composites Strategy* (BIS, 2009), *Zukunftsfeld Werkstofftechnologien* (Lust et al., 2008), and *Materials Science and Engineering in Germany* (acatech, 2008). *The UK Composites Strategy* (BIS, 2009) discusses a brief international comparison to understand how the areas of industrial activity compare to global value chains and extract the UK's competitive advantage. In Germany, the Research Union (Lust et al., 2008) and acatech (2008) identify the fragmentation between materials types in research leading to a fragmentation of firms, clusters, networks, and professional organisations, which users can find difficult to navigate; a trait that is arguably global, but offers possible gains for countries that manage to defragment the industry or support users to navigate it. In general, however, broad configurations of industrial systems were missing.

Despite not focusing on industrial system configuration, many documents paid attention to selected industrial system elements. Of the 24 sample documents, 14 paid some attention to design, 23 paid attention to production, 16 paid attention the sales, and 21 to future market

opportunities (as defined by the above criteria). The only three sample documents to omit market context focused on upstream production (NCN, 2006c), on very early stage research (Materials UK, 2006c), and on 'grand' societal challenges as the purpose of R&D rather than economic markets (EPSRC, 2014).

Of the sample documents, 14 did not pay any attention to at least one industrial system element. Most of these (11) were documents that did not bound their review by industrial sector (see appendix). While it appears that the consideration of industrial system elements tended to be more comprehensive when the document's exploration of advanced materials was bounded by sector (e.g., BIS, 2013a; NCN, 2006b; Sherry et al., 2010), many of the documents that did not define the boundaries of the advanced materials by application sector provided specific instances of these industrial system elements. Examples include defining the domain of the document by the material type composites (BIS, 2009), by structural properties and applications (Materials UK, 2009), and by 'nanoscale technologies' (TSB, 2009). This suggests that identifying industrial system configuration might be easier if the study is bounded by industrial sector.

## 7 Discussion

Even given the variations of purpose (given their objectives, specific context, target audience, etc.) and quality (and possible variations in the 'as-objective-as-possible' assessment of the documents), the categories explored continually emerged as important considerations in the review. These findings suggest there is more identifiable structure in the process of

<sup>5</sup> The German Academy of Science and Engineering (Deutsche Akademie Der Technikwissenschaften, acatech)

<sup>6</sup> The Research Alliance for Industry and Science (Die Forschungsunion Wirtschaft – Wissenschaft)

technological innovation than is typically acknowledged in FTA exercises.

However, it is also evident that the categories received varied attention, suggesting they were either: not important for some exercises; important, but not part of the objectives of the exercise; or overlooked in the underpinning exercise. Evidence that they were overlooked in the underpinning exercise can be drawn from documents' description of the exercise's underpinning conceptual framework, questions used to illicit information, and terms of reference (hereon underpinning architecture). If they emerged despite not being part of this architecture, then they *are* important, but *could* be overlooked. The potential to overlook categories is also illustrated using comparisons between documents, which illustrate that the categories emerged or received more attention in comparable documents, and from the changing nature of innovation with respect to these categories.

The next section will explore the evidence from the review and explore the specific instances where the categories emerged and did not emerge, and why this might be the case. The second section of the discussion will explore how these categories help to apply innovation systems concepts in FTA and how innovation system concepts help to make using these categories useful for STI policy development. The final section outlines further work that could be done.

### Reflecting on the categories used

#### *Technology types*

The review suggests that many of the categories of technology type exist and are relevant for technology development. The enabling technologies, with their role of supporting

knowledge development, received particular attention.

The review suggests that attention to infratechnologies, production technologies, the science base, and generic technologies, with their varying public, quasi-public, and private good content, were not targeted because they had these attributes, but emerged because they were important. (This importance may be because in the past they have failed to attract private investment because of these attributes.) However, when comparing documents it becomes evident that some categories can receive inconsistent attention if not explicitly part of the exercise's underpinning architecture. For example, nanomanufacturing was one of the key programme areas in the US National Nanotechnology Initiative (NSTC, 2011a). However, despite this and despite it being cited many times in the appendix of *Nanotechnology: a UK industry view* (Materials KTN and Materials UK, 2010), production technologies failed to be mentioned in much detail in the report (outside of health and safety).

Given how often the infratechnologies were highlighted in the reviewed, a question should be asked about whether more refined categories should be used. The US *Materials Genome Initiative* (NSTC, 2011b), for example, explicitly aimed to develop a range of infratechnologies to accelerate and reduce the cost of the research design to deployment pathway of novel materials development. The programme management team acknowledge that such an ambitious project will need an integrated set of radically new infratechnologies (e.g., modelling and simulation, new shared databases, measurement, testing, and characterisation tools, and altering design). This programme made further distinctions between sub-categories of infratechnology: computational tools, experimental tools, and digital tools. More

refined categories such as these may be needed in instances where infratechnologies are so important and so prolific for overcoming innovation challenges.

The attention being paid to enabling technologies for advanced materials could be the result of the changing nature of competition and ever increasing technical complexity. As technological competition increases among advanced economies, so too does the interest in accelerating innovation, placing greater emphasis on the infratechnologies and production technologies that enable development and deployment. Furthermore, technical complexity is advancing to the point where bespoke advanced materials are requiring more specific and customised infratechnologies (e.g., measurement, characterisation, and simulation tools) and production technologies (e.g., novel processes, more accurate control).

The importance of the enabling innovation infrastructure – infratechnology and production technologies – indicates that there is merit in building these categories of technology into FTA exercises from the beginning. The explicit inclusion of the technology categories in FTA can help sensitise the people involved and more systematically draw out their implications for both enabling and inhibiting technical knowledge development, diffusion, and use.

#### *Emergence phases and transitions*

The review revealed that the documents also gave attention to phases and transitions, without them being explicitly used to structure the exercise. For example, notions of a technology lifecycle were only implicitly considered in the questions addressed in *Materials R&D for Nuclear Applications* (Sherry et al., 2010); however, the document focused on drawing on novel science to help extend the application of materials already in the early stages of industrial

use to increasingly larger-scale and more sophisticated applications, emphasising the application phase of emergence and the transition to it from the technology phase.

The breadth of phases that received attention generally matched the breadth of the 'domain' with which the document was concerned. The 'domain' could be defined by a combination of: material types, properties, applications, and processing techniques and scales. Sometimes the 'domain' was defined broadly, such as advanced materials, which lead to all phases of development receiving attention (e.g., Materials IGT, 2006); and other times it was defined narrowly, constraining the spread of domain maturity, such as materials for nuclear electricity generation (e.g., Sherry et al., 2010).

In many instances when the domain was very broad, specific phases and transitions received less attention. This suggests that the broader the domain, the less carefully the transitions can be defined and the less the resulting document can worry about lifecycles for ever larger application markets. Vague definitions of the platform, in particular in their application, can make it difficult for policymakers to support transitions between advanced material lifecycle stages in the interest of accelerating innovation.

The view of domains taken here point to a platform view of technology development, where the focus is on developing a body of knowledge that is integrated and deployed in multiple applications and often multiple generations (i.e. resulting in a group of technologies being deployed) (Tassey, 2007). It was for these platforms that the categories of phases and transitions adopted here were developed; Phaal et al. (2011), the origin of the STAM categories, applied them in a case study on synthetic diamond development that resulted in a series of synthetic diamond enabled products.

While a number of documents reviewed identified a conceptual pathway using concepts such as Technology Readiness Levels (e.g., TSB, 2008) or a value chain (e.g., acatech, 2008; Materials IGT, 2006; TSB, 2008), they lacked a conceptual understanding of the development, diffusion, and (re)deployment of a platform technology. This indicates a shift in focus for technology strategies from applications for industrial strategies to platform technologies for publicly-focused strategies.

The intrinsic temporal nature of technological innovation asserts that all future-oriented exercises will inherently focus on some or all of the phases of technology development, which is demonstrated by the review. However, FTA could more carefully target specific phases and transitions by explicitly including the categories used here. These categories draw attention to the centre of innovative activity, which can be used to define the demonstrators, performance criteria, or other requirements needed to diffuse technical knowledge.

#### *Industrial system structure*

As stated, some documents incorporated conceptualisations of the supply chain into their underpinning architecture, from raw materials through to after sales services; and often design (and less often other stages of R&D) were integrated into these (e.g., acatech, 2008; BMBF, 2004; Materials IGT, 2006; TSB, 2008). However, the inclusion of such conceptual structures these views did not always enable configurations of industrial systems to emerge (e.g., Materials IGT, 2006) or even for categories of industrial activities to receive much attention (e.g., TSB, 2008). It's worth noting that attention to various categories in these conceptual structures varied country-to-country. Some comparable German documents (e.g., acatech, 2008; BMBF, 2004) paid more attention to categories of industrial activity, asking the questions of the value they

see in extracting this information for STI policy development.

The industrial system is essential for deploying novel technologies. The implications of the industrial system for advanced materials development are so important that some recognise that it is unfeasible to conduct FTA without considering the industrial system into which it will be deployed. For example, the KET working group on advanced materials said, 'advanced materials are so strongly integrated in and defined by the applications they are serving... that a value chain analysis is unavoidable' (KET AMT, 2010, p. 1). The German Academy of Science and Engineering (acatech, 2008, p. 19) also contended that the development of advanced materials 'cannot be separated' from an appreciation of the physical value-creation stages in the supply chain. The importance of industrial system structure compelled all documents in the review to pay at least some attention to the industrial value capturing activities and their potential (despite most not having a conceptualisation of industrial system elements or configuration in their underpinning architecture).

As with infratechnologies, design was discussed in a number of cases, asking whether sub-categories of design should be drawn on when designing FTA. The review revealed that design was discussed in an alternative way to the new product development and 'industrial design' focus taken in the design category. These alternative views discussed design in terms of the 'bottom-up' design of a material, from the inception of the material itself through simulation, characterisation, and testing through to deployment ('materials by design'). This is the objective of the US *Materials Genome Initiative* (NSTC, 2011b), as discussed earlier, and Japan's *Materials Informatics* initiative (CRDS, 2013). While the review focused on materials design in

new product development, these findings suggest that materials *by design* is also an important concept as it can accelerate innovation and enable the development of entirely new materials. These observations suggest that this form of infratechnology-enabled materials R&D is a different category of design that could have significant implications for future-oriented exercises. Further research might reveal if similar considerations exist (or might exist) in other technical domains.

The motivation for including industrial system elements was to consider how the industrial system might be configured to support the consideration of national value capture. Those that reached for value chain conceptualisations in the review identified necessary conditions for national value capture (and the linking between innovation systems and industrial systems), but not the actual industrial context for value capture. For example, Acatech (2008) was concerned that opportunities for deployment in German industry were being lost at the interfaces between actors conducting basic and more applied research, and in applied research that was not more market oriented, which led to other countries taking the lead in these areas. This observation points to an innovation systems issue – a failure in linkages and structure – as a reason for failing to capture value nationally and identified a possible blocking mechanism that government can choose to influence, but makes the assumption that the industry exists to take the innovation up.

Others drew on reviews of current structures to understand how materials developments might be deployed in existing industrial systems. Sherry et al. (2010), for example, drew on a number of studies related to the nuclear industrial system, such as *The mapping of materials supply chains in the UK's power generation sector* (Court, 2008). This illustrates how such strategies are reaching

for structures of the industrial system that provide context for their studies and *future possible industrial structures* and understand how developments in materials might capture value nationally.

This latter example, which grounds its FTA exercise by using the present as a reference point, suggests that industrial elements (activities) need a configured supply chain context, as initially conceived by Sturgeon (2002), before the location of value added activities can begin to be identified and usefully inform government of the actions it might take to enable and enhance national value capture. While precision in exploring specific industrial system structures might be beyond what FTA can be expected to achieve (Abadie et al., 2010), broad elements and configurations, in the same style as Sturgeon (2002), could help FTA explore issues related to national value capture.

The next section explores the links between these categories and innovation systems concepts in more detail.

### **Supporting and informing innovation systems theory & what it has to say about the role for government**

As we have suggested, there is a complementary relationship between innovation system concepts and the categories drawn on in this paper. Innovation system concepts related to structure (see Edquist, 2005), functions (see Bergek et al., 2010; Hekkert et al., 2007; Johnson, 2001), and market and system failures (see Klein Woolthuis et al., 2005; Smith, 2000) help to carefully articulate the implications of the information drawn out by the categories. The categories that have been introduced provide sub-structure for important aspects of innovation systems configuration and dynamics. In particular, they help to understand how these

innovation system concepts can be applied in FTA exercises.

The review of advanced materials foresight supported the idea that an evolving system of 'infrastructural' technologies needs to be in place to enable the development of novel advanced materials, with supports, which supports Tassey (2005). If key elements of the innovation infrastructure are missing (at the wrong phase in the emergence of a novel technology), it potentially points instances of market failure, innovation system failures, or both. Given the varying levels of (quasi-)public good in these enabling technologies – and the private sectors reluctance to invest in them – these categories merit significant attention from policy makers. In this context, we argue that careful consideration should be given to explicitly highlighting these technology types within the design of any FTA exercise for emerging technologies.

Our review also reinforced the potential importance of distinguishing between key phases in the evolving maturity of emerging materials-based markets. In particular, there appear to be important changes in activities and effort of innovation actor as emerging technologies diffuse into different, larger, more mature markets with different application performance requirements and manufacturing systems. Given the ongoing role of public research and innovation throughout these phases – and the potential for national innovation systems to lose competitive advantage during such transitions – these categories merit significant attention from policy makers. In this context, we argue that careful consideration should be given to explicitly highlighting the potential for emerging industry phase transitions during the initial design of any FTA exercise for emerging technologies.

An investigation of industrial system elements can also enhance the identification of possible

innovation system failures in FTA exercises, particularly when combined with an understanding of innovation dynamics. Understanding the industrial system structure can reveal the industrial system's capability and capacity to adopt and deploy the innovation, helping to compare government options and draw attention to capability failures – the inability to learn or learn quickly enough for an innovation to take hold and be successful (Klein Woolthuis et al., 2005). Furthermore, understanding how the industrial system elements might evolve helps to explore potential market power issues, a *market* failure that could prevent UK firms capitalising on value creation and capture opportunities.

From this discussion it appears that the categories identified lend themselves to supporting the deployment and application of innovation system concepts in FTA. In particular, the distinctions they draw can help draw attention to areas where potential government action could unlock major innovation opportunities. Furthermore, they provide further information to allow governments to assess alternative options for intervention. They provide practical guidance that help governments address the inherent difficulties that have been identified in applying evolutionary theory and innovation systems approaches in practice (Chaminade and Edquist, 2010). Similarly, innovation system concepts enhance how these categories can help FTA generate useful findings for government.

### **Further work**

The categories presented here are by no means complete. Advanced materials was a useful domain to explore these categories in, because its novel functionality and novel molecular structure requires new enabling technologies; it can be deployed in multiple applications (often in different sectors), each with their own lifecycles

and transition challenges; and it enables the development of new product classes, which can disrupt existing industrial value and supply chains. While these attributes helped to demonstrate the categories drawn on here, further work is needed to explore how they apply other non-advanced materials technologies (e.g., technologies from the life sciences, computer sciences, etc.). Furthermore is also needed to explore if these categories are too refined or not refined enough for suitably guiding specific FTA exercises, and how they might be adapted depending on the specific context.

## 8 Conclusion

This paper investigated opportunities to enhance future-oriented analysis of the emergence of novel technologies within innovation systems. In particular, we explored ways FTA might be structured for more detailed investigation of the complex innovation system journeys of such technologies as they are developed, diffuse, and get deployed. To do this we introduced a set of dimensions of analysis not conventionally used within FTA. We drew on concepts from innovation-related management and economics research domains to characterise key structural elements of innovation systems and their dynamics, in particular: (1) 'infrastructural technologies' which may be required to develop emerging technologies; (2) key phases of emergence lifecycles, as technologies diffuse into new application domains and ever larger, more mature markets; and (3) key stages of industrial value chains into which the technologies may get deployed (and where economic value may be captured).

Our review of almost 250 international foresight-related analyses and strategy documents for advanced materials revealed that – although generally used inconsistently and unsystematically within FTA – the proposed

categories do repeatedly emerge as important elements of the evolving innovation system structure, activities and dynamics. This suggests that they are, therefore, potential sources of 'innovation system failure'. The fact that these categories received varying levels of attention – not least from country to country (and agency to agency) – suggests that these underlying structural elements of the innovation process may not always be sufficiently acknowledged in underpinning FTA. Furthermore, advanced materials has the potential to have significant impact in a number of number of possible applications, each with their own path specific challenges; which is similar to many other technologies in the UK's '*Great technologies*', the priority '*Manufacturing Technology Areas*' of the US '*National Advanced Manufacturing Strategy*', and EU's '*Key Enabling Technologies*'.

The overall frequency with which these categories are revealed, however – not least in exercises with clearly articulated boundaries, including application spaces – suggests there may be significant merit in careful consideration of these categories within FTA design. In particular, careful attention to these categories has the potential to reveal sources of innovation system failure that might otherwise be missed, thus helping policy makers design and coordinate policy actions in response. In particular, analyses of these categories have the potential to: reveal the public good nature of different types of technology; focus attention on the challenges of making transitions into increasingly mature markets; and address the absorption potential of value chain activities within national innovation systems. These insights should be invaluable to policy makers in identifying and managing technology R&D portfolios, prioritising investments, and coordinating key innovation agencies, to enable, enhance, and accelerate innovation of emerging technologies.



Although future work should further test and refine the proposed categories of technology, lifecycle and industrial activity, this paper offers a compelling demonstration that they can underpin more detailed analyses of the fundamental structural dynamics of innovation and, consequently, have significant potential to enhance FTA for key emerging technologies.

## References

- Abadie, F., Friedewald, M., Weber, K.M., 2010. Adaptive foresight in the creative content industries: anticipating value chain transformations and need for policy action. *Sci. Public Policy* 37, 19–30.
- acatech, Deutsche Akademie Der Technikwissenschaften (German National Academy of Science and Engineering), 2008. Materials Science and Engineering in Germany: Recommendations on Image Building, Teaching and Research. acatech, München.
- Alkemade, F., Kleinschmidt, C., Hekkert, M., 2007. Analysing emerging innovation systems: a functions approach to foresight. *Int. J. Foresight Innov. Policy* 3, 139–168. doi:10.1504/IJFIP.2007.011622
- Andersen, A.D., Andersen, P.D., 2014. Innovation system foresight. *Technol. Forecast. Soc. Change* 88, 276–286. doi:10.1016/j.techfore.2014.06.016
- Ansoff, H.I., Stewart, J.M., 1967. Strategies for a technology-based business. *Harv. Bus. Rev.* 45, 71–83.
- Arrow, K.J., 1962. Economic welfare and the allocation of resources for invention, in: Nelson, R.R. (Ed.), *The Rate and Direction of Inventive Activity*. Princeton University Press, Princeton, New Jersey, pp. 609–625.
- Bartlett, C.A., Ghoshal, S., 1989. *Managing Across Borders: The Transnational Solution*. Harvard Business School Publishing, Boston, MA.
- Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. *Res. Policy* 37, 407–429. doi:10.1016/j.respol.2007.12.003
- Bergek, A., Jacobsson, S., Hekkert, M.P., Smith, K., 2010. Functionality of innovation systems as a rationale for and guide to innovation policy, in: Smits, R.E., Kuhlmann, S., Shapira, P. (Eds.), *The Theory and Practice of Innovation Policy: An International Research Handbook*, PRIME Series on Research and Innovation Policy in Europe. Edward Elgar, Cheltenham, pp. 115–144.
- Berger, S., 2013. *Making in America: From Innovation to Market*. MIT, Cambridge, MA.
- BIS, Department for Business, Innovation and Skills, Innovation and Skills, 2013a. *Lifting Off - Implementing the Strategic Vision for UK Aerospace, Industrial strategy: government and industry in partnership*. HM Government, London.
- BIS, Department for Business, Innovation and Skills, Innovation and Skills, 2013b. *The UK's Nuclear Future, Industrial strategy: government and industry in partnership*. HMSO, London.
- BIS, Department for Business, Innovation and Skills, Innovation and Skills, 2012. *Advanced Manufacturing Supply Chain Initiative: Forthcoming competition for funding (Advance Notice)*. BIS, London.
- BIS, Department for Business, Innovation and Skills, Innovation and Skills, 2009. *The UK Composites Strategy (Strategy statement)*. BIS, London.
- BMBF, Bundesministeriums für Bildung und Forschung, (Federal Ministry of Education and Research), 2014. *The new High-Tech Strategy: Innovations for Germany*. BMBF, Berlin.
- BMBF, Bundesministeriums für Bildung und Forschung, (Federal Ministry of Education and Research), 2010. *High-Tech Strategy 2020 for Germany: Ideas, Innovation, Prosperity*. BMBF, Bonn.
- BMBF, Bundesministeriums für Bildung und Forschung, (Federal Ministry of Education and Research), 2004. *Materials Innovations for Industry and Society - WING, Framework Programme*. BMBF, Bonn.

- Bowersox, D.J., Closs, D.J., Cooper, M.B., 2007. *Supply Chain Logistics Management*, 2nd ed. McGraw-Hill/Irwin Companies, New York, NY.
- Bush, V., 1945. *Science, the Endless Frontier: a Report to the President*. U.S. Government Printing Office, Washington, D.C.
- Cabinet Office, HM Government, 1993. *Realising our potential: A Strategy for Science, Engineering and Technology* (No. Cm2250). HMSO, London.
- Cagnin, C., Amanatidou, E., Keenan, M., 2012. Orienting European innovation systems towards grand challenges and the roles that FTA can play. *Sci. Public Policy* 39, 140–152. doi:10.1093/scipol/scs014
- Cagnin, C., Keenan, M., 2008. Positioning Future-Oriented Technology Analysis, in: Cagnin, C., Keenan, M., Johnston, R., Scapolo, F., Barré, R. (Eds.), *Future-Oriented Technology Analysis: Strategic Intelligence for an Innovative Economy*. Springer, Berlin & Heidelberg, pp. 1–13.
- Chaminade, C., Edquist, C., 2010. Rationales for Public Policy Intervention in the Innovation Process: Systems of Innovation Approach, in: Smits, R.E., Kuhlmann, S., Shapira, P. (Eds.), *The Theory and Practice of Innovation Policy: An International Research Handbook*. Edward Elgar Publishing Ltd, Cheltenham, pp. 95–114.
- Chopra, S., Meindl, P., 2004. *Supply Chain Management: Strategy, Planning and Operations*, 2nd ed. Pearson Education Ltd, Upper Saddle River, New Jersey.
- Christopher, M., 2005. *Logistics and Supply Chain Management*, 3rd ed. Prentice Hall Inc., Sydney, NSW.
- CLF, Composites Leadership Forum, 2013. *UK Composites 2013: A Study into the Status, Opportunities and Direction for the UK Composites Industry*. Department for Business, Innovation and Skills (BIS), HM Government, London.
- Court, S.A., 2008. *The mapping of materials supply chains in the UK's power generation sector*, Materials UK Energy Review 2008. Materials UK, Rotherham.
- CRDS, Center for Research and Development Strategy, Japan Science and Technology Agency (JST), 2013. *Materials Informatics: Materials Design by Digital Data Driven Method*, Strategic Proposal. JST, Kawaguchi.
- CSTP, Council for Science and Technology Policy, 2010. *Japan's Science and Technology Basic Policy Report (The 4th Basic Plan)*. Bureau of Science and Technology Policy, Cabinet Office, Government of Japan, Tokyo.
- Dosi, G., 1988. The nature of the innovative process, in: Dosi, G., Freeman, C., Nelson, R.R., Soete, L. (Eds.), *Technical Change and Economic Theory*. Pinter Publishers, London.
- Edquist, C., 2005. Systems of innovation: perspectives and challenges, in: Fagerberg, J., Mowery, D.C., Nelson, R.R. (Eds.), *The Oxford Handbook of Innovation*. Oxford University Press, Oxford, pp. 181–208.
- Edquist, C., 1997. System of innovation approaches - their emergence and characteristics, in: Edquist, C. (Ed.), *Systems of Innovation: Technologies, Institutions, and Organizations*. Pinter Publishers, London, pp. 1–35.
- EPSRC, E. and P.S.R.C., 2014. *Engineering Grand Challenges: Report on outcomes of a retreat*. Engineering and Physical Sciences Research Council (EPSRC), Swindon.
- EPSRC, E. and P.S.R.C., 2013. *Materially Better: Ensuring the UK is at the Forefront of Materials Science*. Engineering and Physical Sciences Research Council (EPSRC).
- ESFRI, European Strategy Forum on Research Infrastructures, 2011. *Strategy Report on Research Infrastructures: Roadmap 2010*. ESFRI, Directorate-General for Research & Innovation, European Commission, Brussels.
- ESFRI, European Strategy Forum on Research Infrastructures, 2009. *National Roadmaps for Research Infrastructure*. European Commission, Brussels.
- European Commission, 2012. *A European strategy for Key Enabling Technologies – A bridge to growth and jobs*

- (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions No. COM(2012) 341). European Commission, Brussels.
- Featherston, C., O'Sullivan, E., 2015. The implications of innovation system maturity for the development of national strategies for emerging technologies: lessons and insights from past experiences. Presented at the Atlanta Conference on Science and Technology Policy, Atlanta, GA.
- Featherston, C., O'Sullivan, E., 2014a. A review of international public sector strategies and roadmaps: A case study in materials (A report for the Department of Business, Innovation and Skills (BIS)). Centre for Science, Technology & Innovation Policy (CSTI), University of Cambridge Institute for Manufacturing (IfM), Cambridge.
- Featherston, C., O'Sullivan, E., 2014b. National and regional public technology strategies: exploring practice using the Science-Technology-Application-Market (STAM) Typology. Presented at the 5th International Conference on Future-Oriented Technology Analysis (FTA), Brussels.
- Galli, R., Teubal, M., 1997. Paradigmatic shifts in national innovation systems, in: Edquist, C. (Ed.), *Systems of Innovation: Technologies, Institutions, and Organizations*. Pinter Publishers, London.
- Georghiou, L., 1996. The UK technology foresight programme. *Futures* 28, 359–377.
- Gort, M., Klepper, S., 1982. Time paths in the diffusion of product innovations. *Econ. J.* 92, 630–653.
- Government of Japan, 2016. The 5th Science and Technology Basic Plan, translation. ed. Council for Science, Technology, and Innovation (CSTI), Cabinet Office, Government of Japan.
- Groenveld, P., 1997. Roadmapping integrates business and technology. *Res.-Technol. Manag.* 40, 48–55.
- Harland, C.M., 1996. Supply Chain Management: relationships, chains and networks. *Br. Acad. Manag.* 7, 63.
- Harrington, T.S., Srai, J.S., 2014. Supply network emergence models and the development of nascent and emerging industries. Presented at the Production and Operations Management Conference, Atlanta, GA.
- Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: a new approach for analysing technological change. *Technol. Forecast. Soc. Change* 74, 413–432.  
doi:10.1016/j.techfore.2006.03.002
- Hines, P., Rich, N., 1997. The seven value stream mapping tools. *Int. J. Oper. Prod. Manag.* 17, 46–64.  
doi:10.1108/01443579710157989
- HLG KET, High-Level Expert Group on Key Enabling Technologies, 2015. KETs: Time to Act (Final report). European Commission, Brussels.
- HLG KET, High-Level Expert Group on Key Enabling Technologies, 2014. KETs for a competitive Europe. European Commission, Brussels.
- HLG KET, High-Level Expert Group on Key Enabling Technologies, Directorate General Enterprise and Industry, 2011. High-Level Expert Group on Key Enabling Technologies: Final Report. European Commission, DG Enterprise and Industry, Brussels.
- HM Government, 2010. UK Nanotechnologies Strategy: Small Technologies, Great Opportunities (No. URN 10/825). HM Government, London.
- House of Commons, Public Administration Select Committee, HM Government, 2010. Who does UK National Strategy? (First Report of Session 2010–11). The Stationery Office, London.
- Innovate UK, 2014. Emerging technologies and industries strategy 2014-2018. Innovate UK, Swindon.
- IoM3, T.I. of M., Minerals and Mining, 2010. Roadmap on Nanomaterials in Polymer Applications for the Transport Industry. The Institute of Materials, Minerals and Mining (IoM3), London.

- Johnson, A., 2001. Functions in innovation system approaches. Presented at the DRUID's Nelson-Winter Conference, Aalborg, Denmark.
- KET AMT, Key Enabling Technologies working group on Advanced Materials Technologies, 2010. Working Group on Advanced Materials Technologies (working document). Directorate General Enterprise and Industry (DG-El), European Commission.
- Klein Woolthuis, R., Lankhuizen, M., Gilsing, V., 2005. A system failure framework for innovation policy design. *Technovation* 25, 609–619.  
doi:10.1016/j.technovation.2003.11.002
- Link, A.N., Scott, J.T., 2013. The theory and practice of public-sector R&D economic impact analysis, in: Link, A.N., Vonortas, N.S. (Eds.), *Handbook on the Theory and Practice of Program Evaluation*. Edward Elgar, Cheltenham, pp. 15–55.
- Link, A.N., Scott, J.T., 2011. *Public Goods, Public Gains: Calculating the Social Benefits of Public R&D*. Oxford University Press, New York, NY.
- Livesey, F., 2012. Rationales for industrial policy based on industry maturity. *J. Ind. Compet. Trade* 12, 349–363.  
doi:10.1007/s10842-011-0103-8
- Lust, K.-H., Hanselka, H., Eul, U., 2008. *Zukunftsfeld Werkstofftechnologien (The Future of Materials Science)*. Die Forschungsunion Wirtschaft – Wissenschaft (The Research Alliance for Industry and Science), with support from the Fraunhofer Materials and Components Group - Fraunhofer VWB.
- Markard, J., Hekkert, M., Jacobsson, S., 2015. The technological innovation systems framework: Response to six criticisms. *Environ. Innov. Soc. Transit.* 16, 76–86.  
doi:10.1016/j.eist.2015.07.006
- Mateos-Garcia, J., Geuna, A., Steinmueller, W.E., 2008. State of the art of the european creative content industry and market and national/industrial initiatives, in: *The Future Evolution of the Creative Content Industries: Three Discussion Papers*. Office for Official Publications of the European Communities, Luxembourg, pp. 5–72.
- Materials IGT, Materials Innovation and Growth Team, 2006. *A Strategy for Materials*. Department of Trade and Industry (DTI), HM Government, London.
- Materials KTN, Materials Knowledge Transfer Network, Technology Strategy Board (TSB) & Materials UK, 2010. *Nanotechnology: a UK industry view*. Materials Knowledge Transfer Network, Nanotechnology Knowledge Transfer Network & Materials UK.
- Materials UK, 2009. *Structural materials - A Science and Technology Report*. Materials UK.
- Materials UK, 2006a. *Functional Materials*. Department of Trade and Industry (DTI), London.
- Materials UK, 2006b. *Biomaterials*. Department of Trade and Industry (DTI), London.
- Materials UK, 2006c. *Multifunctional Materials*. Department of Trade and Industry (DTI), London.
- Materials UK, namtec, National Metals Technology Centre, 2006. *Structural Materials*. Department of Trade and Industry (DTI), HM Government, London.
- Miles, I., 2005. UK Foresight: three cycles on a highway. *Int. J. Foresight Innov. Policy* 2, 1–34.
- Miles, I., Cassingena Harper, J., Georghiou, L., Keenan, M., Popper, R., 2008. The many faces of foresight, in: Georghiou, L., Cassingena Harper, J., Keenan, M., Miles, I., Popper, R. (Eds.), *The Handbook of Technology Foresight: Concepts and Practice*, PRIME Series on Research and Innovation Policy. Edward Elgar Publishing, Cheltenham, pp. 3–23.
- Miller, D., Friesen, P.H., 1984. A Longitudinal Study of the Corporate Life Cycle. *Manag. Sci.* 30, 1161–1183.  
doi:10.1287/mnsc.30.10.1161
- NCN, N.C.N., 2006a. *Technology Roadmap for Composites in the Aerospace Industry*. Materials Knowledge Transfer Network & Department of Trade and Industry, HM Government, Cambridge.
- NCN, National Composites Network, 2006b. *Technology Roadmap for Composites in the Marine Industry*. Materials Knowledge Transfer Network &

- Department of Trade and Industry, HM Government, Cambridge.
- NCN, National Composites Network, 2006c. Technology Roadmap for the Metal Matrix Composites Industry. Materials Knowledge Transfer Network & Department of Trade and Industry, HM Government, Cambridge.
- NCN, National Composites Network, 2006d. Technology Roadmap for Composites in the Construction Industry. Materials Knowledge Transfer Network & Department of Trade and Industry, HM Government, Cambridge.
- NCN, National Composites Network, 2005. Technology Roadmap for Composites in the Automotive Industry. Materials Knowledge Transfer Network & Department of Trade and Industry, HM Government, Cambridge.
- Nelson, R.R., 1959. The simple economics of basic scientific research. *J. Polit. Econ.* 67, 297–306.
- Nelson, R.R., Winter, S.G., 1982. *An Evolutionary Theory of Economic Change*. Harvard University Press, Cambridge, MA.
- NIST, National Institute of Standards and Technology, 2006. *An Assessment of the United States Measurement System: Addressing Measurement Barriers to Accelerate Innovation*. NIST, U.S. Department of Commerce, Gaithersburg, MD.
- NSTC, National Science and Technology Council, 2014. *National Nanotechnology Initiative: Strategic Plan*. Executive Office of the President of the United States (EOP), Washington, D.C.
- NSTC, National Science and Technology Council, Executive Office of the President, 2011a. *National Nanotechnology Initiative: Strategic Plan*. Executive Office of the President of the United States (EOP), Washington, D.C.
- NSTC, National Science and Technology Council, 2011b. *Materials Genome Initiative for Global Competitiveness*. Executive Office of the President of the United States (EOP), Washington, D.C.
- PCAST, President's Council of Advisors on Science and Technology, 2014. *Report to the President: Accelerating U.S. Advanced Manufacturing*. Executive Office of the President of the United States (EOP), Washington, D.C.
- PCAST, President's Council of Advisors on Science and Technology, 2012. *Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing*. Executive Office of the President of the United States (EOP), Washington, D.C.
- Peppard, J., Rylander, A., 2006. From value chain to value network: insights for mobile operators. *Eur. Manag. J.* 24, 128–141. doi:10.1016/j.emj.2006.03.003
- Phaal, R., Farrukh, C.J.P., Probert, D.R., 2010. Roadmapping for Strategy and Innovation: Aligning Technology and Markets in a Dynamic World. University of Cambridge, Institute for Manufacturing, Cambridge.
- Phaal, R., Farrukh, C.J.P., Probert, D.R., 2004. Technology roadmapping—A planning framework for evolution and revolution. *Technol. Forecast. Soc. Change* 71, 5–26. doi:10.1016/S0040-1625(03)00072-6
- Phaal, R., Muller, G., 2009. An architectural framework for roadmapping: Towards visual strategy. *Technol. Forecast. Soc. Change* 76, 39–49. doi:10.1016/j.techfore.2008.03.018
- Phaal, R., O'Sullivan, E., Routley, M.J., Ford, S.J., Probert, D.R., 2011. A framework for mapping industrial emergence. *Technol. Forecast. Soc. Change* 78, 217–230. doi:10.1016/j.techfore.2010.06.018
- Porter, A.L., 2010. Technology foresight: types and methods. *Int. J. Foresight Innov. Policy* 6, 36–45.
- Porter, A.L., Ashton, W.B., Clar, G., Coates, J.F., Cuhls, K., Cunningham, S.W., Ducatel, K., van der Duin, P., Georghiou, L., Gordon, T., Linstone, H.A., Marchau, V., Massari, G., Miles, I., Mogee, M., Salo, A., Scapolo, F., Smits, R.E., Thissen, W., 2004. *Technology futures analysis: Toward integration of the field and new methods*. *Technol. Forecast. Soc. Change* 71, 287–303. doi:10.1016/j.techfore.2003.11.004
- Porter, M.E., 1998. *Competitive Advantage of Nations*, 2nd ed. Free Press, New York, NY.

- Porter, M.E., 1985. *Competitive Advantage: Creating and Sustaining Superior Performance*. Free Press, New York, NY.
- Radar, M., Porter, A.L., 2008. Fitting future-oriented technology analysis methods to study types, in: Cagnin, C., Keenan, M., Johnston, R., Scapolo, F., Barré, R. (Eds.), *Future-Oriented Technology Analysis: Strategic Intelligence for an Innovative Economy*. Springer, Berlin & Heidelberg, pp. 20–40.
- RCUK, Research Councils UK, 2012. *Investing for growth: Capital Infrastructure for the 21st Century*. Research Councils UK (RCUK), Swindon.
- RCUK, Research Councils UK, 2010. *Large Facilities Roadmap 2010*. Research Councils UK (RCUK), Swindon.
- RCUK, Research Councils UK, 2007. *Increasing the Economic Impact of the Research Councils*. Research Councils UK (RCUK), London.
- Rosenberg, N., 1996. Uncertainty and technological change, in: *Technology and Growth: Conference Proceedings*. Presented at the Technology and Growth, pp. 91–110.
- Sainsbury, D., 2007. *The Race to the Top: A Review of Government's Science and Innovation Policies (The Sainsbury Review)*. HMSO, Norwich.
- Scapolo, F., Cahill, E., 2004. *New Horizons and Challenges for Future-oriented Technology Analysis: proceedings of the EU–US scientific seminar: new technology foresight, forecasting & assessment methods (Technical Report Series No. EUR 21473 EN)*. European Commission, Brussels.
- Sherry, A.H., English, C.A., Flewitt, P.E.J., 2010. *Materials R&D for Nuclear Applications: The UK's Emerging Opportunities (Report 6)*, Materials UK Energy Review 2010. Materials UK, Manchester.
- Shih, S., 1996. *Me-Too is Not My Style: Challenge Difficulties, Break through Bottlenecks, Create Values*. The Acer Foundation, Taipei, Taiwan.
- Smith, K., 2000. Innovation as a systemic phenomenon: rethinking the role of policy. *Enterp. Innov. Manag. Stud.* 1, 73–102.
- Srai, J.S., Christodoulou, P., Harrington, T.S., 2014. Configuring global value networks within industrial ecosystems, in: Srai, J.S., Christodoulou, P. (Eds.), *Capturing Value from Global Networks: Strategic Approaches to the Design of International Production, Supply and Service Operations*. University of Cambridge, pp. 38–51.
- Srai, J.S., Gregory, M., 2008. A supply network configuration perspective on international supply chain development. *Int. J. Oper. Prod. Manag.* 28, 386–411. doi:10.1108/01443570810867178
- Sturgeon, T.J., 2002. Modular production networks: a new American model of industrial organization. *Ind. Corp. Change* 11, 451–496.
- Sturgeon, T.J., 2001. How Do We Define Value Chains and Production Networks? *IDS Bull.* 32, 9–18.
- Tassey, G., 2010. Rationales and mechanisms for revitalizing US manufacturing R&D strategies. *J. Technol. Transf.* 35, 283–333. doi:10.1007/s10961-009-9150-2
- Tassey, G., 2008. Modeling and measuring the economic roles of technology infrastructure. *Econ. Innov. New Technol.* 17, 615–629. doi:10.1080/10438590701785439
- Tassey, G., 2007. *The Technology Imperative*. Edward Elgar, Cheltenham.
- Tassey, G., 2005. Underinvestment in public good technologies. *J. Technol. Transf.* 30, 89–113.
- Tassey, G., 2003. *Methods for Assessing the Economic Impacts of Government R&D (Planning Report 03-1)*. National Institute of Standards and Technology (NIST), Gaithersburg, MD.
- Tassey, G., 1991. The functions of technology infrastructure in a competitive economy. *Res. Policy* 20, 345–361. doi:10.1016/0048-7333(91)90094-7
- TSB, Technology Strategy Board, 2009. *Nanoscale Technologies Strategy 2009–12*. Technology Strategy Board (TSB), Swindon.
- TSB, Technology Strategy Board, 2008. *Key Technology Area: Advanced Materials 2008–2011*. Technology Strategy Board (TSB), Swindon.

- US Committee on Science, U.S.H. of R., 1998. *Unlocking Our Future: Toward a New National Science Policy* (No. GPO-CPRT-105). House of Representatives, U.S. Government, Washington, D.C.
- Van de Ven, A.H., 1993. The emergence of an industrial infrastructure for technological innovation. *J. Comp. Econ.* 17, 338–365.  
doi:10.1006/jcec.1993.1029
- Weber, K.M., Cassingena Harper, J., Könnölä, T., Barceló, V.C., 2012. Coping with a fast-changing world: Towards new systems of future-oriented technology analysis. *Sci. Public Policy* 39, 153–165.  
doi:10.1093/scipol/scs012
- Wieczorek, A.J., Hekkert, M.P., 2012. Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. *Sci. Public Policy* 39, 74–87.  
doi:10.1093/scipol/scr008
- Willems, R.H.D.M., 2013. Speech: Eight great technologies.
- Yasunaga, Y., Watanabe, M., Korenaga, M., 2009. Application of technology roadmaps to governmental innovation policy for promoting technology convergence. *Technol. Forecast. Soc. Change* 76, 61–79.  
doi:10.1016/j.techfore.2008.06.004

## Acknowledgements

Thanks are due to The Gatsby Foundation for their financial support. Thanks also due to two anonymous reviewers who helped to refine and more clearly articulate the messages in the article.

## Appendix

During the review, a number of observations were made about the roles that various organisations and individuals had in the development and publishing of the programme, strategy, and evidence documents. The observed roles included: a funder (providing funds for the exercise of development), a resource provider (e.g. person days), a driver (i.e. the 'motivator' or the organisation that pushed for the programme, strategy, or evidence document to be developed), a facilitator, a publisher (sometimes different to the driver, such as a parent organisation), and a target audience. Each of these are likely to have influenced the document in different ways.

The organisations that were observed to take on these roles varied, but included: government departments; non-regulatory agencies (US), such as the National Institute of Standards and Technology, and non-departmental public bodies (UK), such as the UK Research Councils; learned organisations (e.g. US National Academies, the UK Royal Society or Royal Academy of Engineering, the German Academy of Science and Engineering – acatech); industry associations (e.g. Germany's Research Alliance for Industry and Science<sup>7</sup>); other official advisory bodies, such as a UK Sector Councils; and selected networks and groups of advanced materials researchers and developers (e.g. UK's Knowledge Transfer Network). As an example the target audience(s) of the 24 sample documents are included in Table 2.

<sup>7</sup> Die Forschungsunion Wirtschaft – Wissenschaft (Forschungsunion)

Document	Driving organisation (facilitating)	Target audience(s)	Document type	Technology types				
				Base science	Generic technology	Proprietary technology	Infra-technology	Production technology
Technology Roadmap for Composites in the Automotive Industry (NCN, 2005)	Materials KTN	Respective industries & R&D communities; composites researchers; government; local & international customers	Evidence document (based on FTA)	1	1	2	1	1
Technology Roadmap for Composites in the Aerospace Industry (NCN, 2006a)	Materials KTN		Evidence document (based on FTA)	1	1	1	3	3
Technology Roadmap for Composites in the Construction Industry (NCN, 2006d)	Materials KTN		Evidence document (based on FTA)	1	1	1	3	2
Technology Roadmap for Composites in the Marine Industry (NCN, 2006b)	Materials KTN	Marine industry	Evidence document (based on FTA)	1	2	1	0	2
Technology Roadmap for the Metal Matrix Composites Industry (NCN, 2006c)	Materials KTN	Customers, public, R&D community	Evidence document (based on FTA)	1	2	1	1	1
Roadmap on Nanomaterials in Polymer Applications for the Transport Industry (IoM3, 2010)	Materials KTN	Government, R&D community, firms in or that use nanotech.	Evidence document (based on FTA)	3	2	3	2	1
Nanotechnology: a UK Industry View (Materials KTN and Materials UK, 2010)	Materials UK & Materials KTN	Government, R&D community, firms in or that use nanotech.	Evidence document (based on FTA)	1	0	2	2	2
Materially Better: Ensuring the UK is at the Forefront of Materials Science (EPSRC, 2013)	EPSRC & BIS	UK materials R&D community	Evidence document (based on FTA)	3	2	1	3	2
Engineering Grand Challenges: Report on outcomes of a retreat (EPSRC, 2014)	EPSRC	Engineering community	Programme evidence document	3	0	0	3	2
Key Technology Area: Advanced Materials 2008-2011 (TSB, 2008)	TSB	UK materials community, particularly R&D	Programme(s) strategy	1	1	0	2	1
Nanoscale Technologies Strategy 2009-12 (TSB, 2009)	TSB	Government, research councils, Innovate UK, industry	Programme(s) strategy	2	2	2	2	3
Materials R&D for Nuclear Applications: The UK's Emerging Opportunities (Sherry et al., 2010)	Materials UK	Nuclear industry/ energy sector	Technology strategy	3	2	0	2	2
A Strategy for Materials (Materials IGT, 2006)	Materials IGT & DTI	UK materials community	Technology strategy	1	1	1	2	1
Functional materials (Materials UK, 2006a)	Materials UK	UK materials community	Evidence document (based on FTA)	3	2	0	3	2
Multifunctional materials (Materials UK, 2006c)	Materials UK	UK materials community	Evidence document (based on FTA)	2	0	0	1	1
Biomaterials (Materials UK, 2006b)	Materials UK	UK materials community	Evidence document (based on FTA)	3	2	1	2	2
Structural materials (Materials UK and namtec, 2006)	Materials UK, DTI & namtec	UK materials community	Evidence document (based on FTA)	1	2	0	2	1
Structural materials - A Science and Technology Report (Materials UK, 2009)	Materials UK	UK materials community	Evidence document (based on FTA)	1	2	0	2	1
UK Composites 2013 (CLF, 2013)	Composites Leadership Forum	UK composites industry	Evidence document (based on FTA)	1	3	0	1	1
The UK Composites Strategy (BIS, 2009)	BIS	UK composites industry & overseas customers	Technology strategy	0	2	2	0	2
Eight Great Technologies (Willets, 2013)	BIS	All	Technology strategy	1	2	1	2	2
UK Nanotechnologies Strategy (HM Government, 2010)	BIS, DEFRA, DH, DWP	R&D community	Technology strategy	1	2	1	2	1
The UK's Nuclear Future (BIS, 2013b)	BIS	Nuclear Industry	Sector strategy	0	1	2	2	2
Lifting Off (BIS, 2013a)	BIS	Aerospace industry	Sector strategy	0	1	0	2	2

Table 2: The types of technology focused on by the programme and strategy documents (UK extract)



Document	Industrial emergence phase				Notes about transitions mentioned in the document
	Science	Technology	Application	Market	
Technology Roadmap for Composites in the Automotive Industry (NCN, 2005)	0	1	2	2	Strong focus on bringing down cost, creating economies of scale, establishing high volume demonstrator, and expanding application (A-M).
Technology Roadmap for Composites in the Aerospace Industry (NCN, 2006a)	0	2	2	2	Discusses using demonstrators to help with transitions. Focus on product, functionality, and cost (T-A & A-M)
Technology Roadmap for Composites in the Construction Industry (NCN, 2006d)	0	3	3	3	Discusses demonstrators to help with transitions. The stronger emphasis on standards indicates a need to demonstrate the functionality of the technology (T-A). E.g., 'must take a lead in showing what is possible' (p.11) & developing 'harmony' with other materials.
Technology Roadmap for Composites in the Marine Industry (NCN, 2006b)	0	2	2	2	Emphasis on the transition from composites applied in other industries to marine (T-A). Also to improve cost structures to shift to larger applications (as mass market as marine can be)
Technology Roadmap for the Metal Matrix Composites Industry (NCN, 2006c)	0	2	3	3	Strong focus on reducing costs or materials (e.g. fibres) and manufacturing, and concern with access to US market, which the report claims is larger (A-M)
Roadmap on Nanomaterials in Polymer Applications for the Transport Industry (IoM3, 2010)	0	3	3	2	In many instances they seem to have demonstrated the functionality, but show that functionality can work reliably in the identified applications. Then they can shift the focus to cost. 'Cost and scale of production will be a major factor in acceptance of nanomaterials' (p.14). Mainly T & beginning to look T-A. Then look at production numbers A-M.
Nanotechnology: a UK Industry View (Materials KTN and Materials UK, 2010)	1	1	1	2	Talk of manufacturing demonstrators to show high volume production capabilities (T-A and A-M). Furthermore, talk of standardisation would help to support these transitions.
Materially Better: Ensuring the UK is at the Forefront of Materials Science (EPSRC, 2013)	1	2	2	0	Discusses connecting EPSRC programmes (Physical Sciences with Manufacturing the Future and Engineering) and suggests that 'the community should take "pathways to impact" more seriously' (p.21) to support the further development and transitions of materials R&D. Finally, argues that new tools and techniques (infratechnologies) can also support transitions.
Engineering Grand Challenges: Report on outcomes of a retreat (EPSRC, 2014)	3	2	0	0	Transition from observation of novel materials phenomena to application in performance.
Key Technology Area: Advanced Materials 2008-2011 (TSB, 2008)	0	1	3	2	Programmes to progress through to thinking about price-point (indicates transition)
Nanoscale Technologies Strategy 2009-12 (TSB, 2009)	0	2	2	0	Programmes to progress through thinking about performance to price-point (indicates transition)
Materials R&D for Nuclear Applications: The UK's Emerging Opportunities (Sherry et al., 2010)	0	2	3	NA*	Focus on competition in main markets (no mass market)
A Strategy for Materials (Materials IGT, 2006)	0	1	1	1	Not much of a focus on transitions, much more general
Functional materials (Materials UK, 2006a)	3	3	1	1	Suggests strategic programmes to support further development (& by implication transitions) of novel phenomena (S-T) & discusses demonstrating particular functional qualities (e.g. quantum cascade lasers)
Multifunctional materials (Materials UK, 2006c)	1	1	0	0	Mentions of transition only from the science base to demonstrate functionality (S-T) and reliability in application (T-A).
Biomaterials (Materials UK, 2006b)	3	3	1	1	A strong focus on clinical testing, which is defined as the critical transition (T-A). Many biomaterials had (at this stage) undesired side-effects and the inability to sustain functionality in vivo.
Structural materials (Materials UK and namtec, 2006)	0	2	3	3	Mentions the use of regulation as a common source of motivation for transitioning. Discusses aligning EU & UK priorities to ensure funding for demonstrators, suggests a consistent and explicit research strategy would support transitioning, and that further developing infratechnologies (e.g. modelling) would also help transition through the phases of development. A focus on new functionality in new materials and combining materials (T-A) and cost reduction (A-M)
Structural materials - A Science and Technology Report (Materials UK, 2009)	0	2	3	3	
UK Composites 2013 (CLF, 2013)	0	2	2	1	Focus on deepening current gains in functionality in the supply chain, disseminating the functional achievements and driving down costs in the supply chain (T-A)
The UK Composites Strategy (BIS, 2009)	0	2	3	3	Strong focus on developing performance (T-A) and price-performance (A-M)
Eight Great Technologies (Willets, 2013)	2	2	1	0	Novel materials and novel functionality (S-T), with some market deployment
UK Nanotechnologies Strategy (HM Government, 2010)	1	2	3	2	Demonstrators and scale-up of laboratory approaches to making nanoscale materials (T-A) and expanding markets for recent gains in nanomaterial functionality (T-A & A-M)
The UK's Nuclear Future (BIS, 2013b)	0	1	3	NA*	Focus on competition in main markets (no mass market)
Lifting Off (BIS, 2013a)	1	2	3	2	Focus on novel functionality (performance) (T-A) and its position in the market (price-performance) (A-M)

Table 3: The phases and transitions focused on by the programme and strategy documents (UK extract)

\* nuclear power stations are not sold to a 'mass-market' to the same degree as many of the other industrial systems

NB: A draft of this table was presented in Featherston &amp; O'Sullivan (2014b)

Document	Deployment industry (if identified)	Industrial system elements & market context			
		Design	Manufacturing	Sales	Market
Technology Roadmap for Composites in the Automotive Industry (NCN, 2005)	Various, but only very brief attention to specific sectors (not just automotive)	0	2	1	1
Technology Roadmap for Composites in the Aerospace Industry (NCN, 2006a)	Aerospace	1	2	1	1
Technology Roadmap for Composites in the Construction Industry (NCN, 2006d)	Construction	0	1	0	1
Technology Roadmap for Composites in the Marine Industry (NCN, 2006b)	Marine, with varying customer classes (performance vs enthusiasts)	3	3	3	3
Technology Roadmap for the Metal Matrix Composites Industry (NCN, 2006c)	Does not identify a deployment sector	1	1	0	0
Roadmap on Nanomaterials in Polymer Applications for the Transport Industry (IoM3, 2010)	Transport applications, e.g. the rail industrial system	2	2	0	1
Nanotechnology: a UK Industry View (Materials KTN and Materials UK, 2010)	Various	0	2	1	3
Materially Better: Ensuring the UK is at the Forefront of Materials Science (EPSRC, 2013)	Various	1	1	1	2
Engineering Grand Challenges: Report on outcomes of a retreat (EPSRC, 2014)	Not identified	1	1	0	0
Key Technology Area: Advanced Materials 2008-2011 (TSB, 2008)	Various	1	2	1	2
Nanoscale Technologies Strategy 2009-12 (TSB, 2009)	Various	2	2	2	3
Materials R&D for Nuclear Applications: The UK's Emerging Opportunities (Sherry et al., 2010)	Nuclear, mostly electricity production	3	3	1	3
A Strategy for Materials (Materials IGT, 2006)	Various, including security, various industrial systems related to energy	0	1	1	2
Functional materials (Materials UK, 2006a)	Various, including ICT, transport, healthcare, defence	0	1	0	3
Multifunctional materials (Materials UK, 2006c)	Various, including energy, defence, healthcare, & security	0	1	0	0
Biomaterials (Materials UK, 2006b)	Mostly healthcare, but others	2	2	0	2
Structural materials (Materials UK and namtec, 2006)	Various, including defence & transport	2	1	2	2
Structural materials - A Science and Technology Report (Materials UK, 2009)	Various, including defence & transport	0	1	2	2
UK Composites 2013 (CLF, 2013)	Various	1	3	2	2
The UK Composites Strategy (BIS, 2009)	Various (acknowledges that there is no composites industry per se)	1	2	2	3
Eight Great Technologies (Willems, 2013)	Various	0	1	1	1
UK Nanotechnologies Strategy (HM Government, 2010)	Various	0	1	0	3
The UK's Nuclear Future (BIS, 2013b)	Nuclear, mostly for electricity production	0	2	2	3
Lifting Off (BIS, 2013a)	Aerospace	2	3	3	3

Table 4: The activities in the value chain focused on by the programme and strategy documents (UK extract)