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

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ABSTRACT

This paper investigates opportunities to enhance Future-oriented Technology Analysis (FTA) of emerging technologies within innovation systems. We address key challenges faced by policymakers developing innovation strategies for emerging technologies. In particular, we explore ways that FTA might be structured to investigate the complex innovation system journeys of novel technologies as they are developed, diffused, and deployed. In doing this, we draw on concepts from technology and operations management and related literatures to more carefully characterise the: (1) 'technical infrastrucutre' 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 find that – although generally used inconsistently and unsystematically within FTA – these categories repeatedly emerge as important elements in many policies, strategies, and underpinning foresight exercises. 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 policymakers coordinate policy actions in response.

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, diffused, and deployed in evolving industrial and market contexts. In particular, we focus on the role of FTA in supporting innovation system policymaking 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 have the potential to reveal important categories of 'innovation system failure', where there may be a role for government.

Key emerging 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, 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/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.

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Given the complexity of emerging technology innovation journeys, the range of potential future outcomes and impacts, and the possible 'failures' that can block their development, government policy design needs to structure and navigate this complexity and anticipate possible challenges, opportunities, and appropriate roles for government. 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 Miles et al. (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[1] — a set of tried and tested future-oriented frameworks and methodologies that can be used to underpin policy design processes.

FTA has proven a valuable tool for informing a range of science, technology, and innovation (STI) policy domains. Formal FTA can be an important informant for government technology strategy,[2] policy, and programme development (Cagnin and Keenan, 2008). These analyses help 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.

However, many important emerging technology-based applications are becoming more technically sophisticated and knowledge-intensive, are being produced by more complex manufacturing systems (as stated), and their complex innovation journeys are becoming harder to understand. 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 gain competitive advantage by bringing these technologies to market early, and, in many cases, 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 deployment of new knowledge).

The increasing technological and manufacturing complexity, the pace of technical change, and growing competition challenge us to explore barriers to emerging technology innovation 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, that merit more direct attention within FTA?

In this paper, therefore, we explore the potential for new FTA dimensions of analysis to help FTA exercises navigate the changing nature of innovation. In particular, we investigate the potential importance of key structural elements related to the innovation journeys of novel technologies as they are developed, diffused, and deployed. In doing this, we draw on concepts from technology and operations management and related literatures to more carefully characterise: (1) 'technical infrastructure' 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, 2011, 2013; 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), we explore the recent evolution of FTA — how it has drawn on innovation system concepts to date and how it motivates a deeper look into the nature (and structural elements) of innovation. We draw on categories, dimensions, and structures provided by other academic literatures — in particular the economics of emerging technologies and innovation, technology management, and operations management - and in Sections 3 to 5 explore the potential of these to more systematically structure FTA exercises for key emerging technologies.

In Section 6, we investigate the extent to which these categories are already used within national FTA exercises. In particular, we review over 240 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). In particular, we observe that many of the proposed categories repeatedly emerge as important elements in many final foresight reports and strategies, but are applied inconsistently and unsystematically in the underpinning FTA exercises.

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, draws 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. The innovation systems perspective 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 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 (e.g., Alkemade et al., 2007; 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 the 'market' and 'system' perspectives help explore the role

[1] 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 includes technology roadmapping and technology intelligence (Porter, 2010; Radar and Porter, 2008).

[2] 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, 2011a) — the development of a strategy can even be the core objective of the programme (Featherston and O'Sullivan, 2015).