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Mediating and catalysing innovation: A framework for anticipating the standardisation needs of emerging technologies

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ABSTRACT

The development of technology strategies are often supported by strategic frameworks. Although standards can be critical in fostering technological innovation, particularly by supporting knowledge diffusion, their importance is often neglected by commonly used strategic frameworks. This paper presents a framework which uses the knowledge that needs to transition between key anticipated innovation activities to anticipate potential standardisation needs for emerging technologies. The framework draws attention to strategic considerations and dimensions that might otherwise be overlooked, including different types of standards; standardisation stakeholders; the alignment, coordination, and sequencing of standards; and how these all change over time. A technology roadmapping based framework was used because it explicitly characterises the alignment, coordination, and sequencing of innovation activities (over time) and can be configured to draw out information against the other above strategic considerations and dimensions. The principles and utility of the framework are demonstrated in three contrasting case studies: synthetic biology, additive manufacturing, and smart grid. These show how standards mediate between innovation actors by codifying and diffusing knowledge and can enhance and catalyse innovation. The proposed framework can be used to reveal where standards might be used to support innovation, better characterise the types of standards needed, identify the stakeholders needed to develop them, and highlight any potential alignment, coordination, and sequencing issues related to standardisation activities.

1. Introduction

Many national governments and executive agencies are taking strategic approaches to supporting key emerging technologies in order to accelerate economic growth and overcome social and environmental challenges (Willetts, 2013; NSTC, 2011a, 2014; HLG KET, 2011). At the same time, there is growing understanding of the role and importance of standardisation in technological innovation, and the potential for technical standards to offer a source of competitive advantage in new industries (Swann, 2010; Bergek et al., 2008; Tassey, 2000; Ehrnberg and Jacobsson, 1997; Smith, 1997; Metcalfe and Miles, 1994; Van de Ven, 1993a; Lundvall, 1992). Of particular interest to national governments and supranational bodies (e.g. CEN, CENELEC, 2014; 2012; Heseltine, 2012; European Commission, 2011) are the opportunities standards offer to help codify diverse types of technical knowledge, which can be important from the very earliest stages of emerging technology innovation and relevant to a range of different innovation activities and actors (Swann, 2010; Blind and Gauch, 2009; Sherif, 2001; Tassey, 2000).

Although standardisation is increasingly highlighted in governmental policies for emerging technologies and associated foresight analyses (NSTC, 2014; TSB, 2012; Bourell et al., 2009), only recently have attempts been made to identify standardisation needs and challenges in a systematic and comprehensive way (e.g. SASAM, 2014; Scapolo et al., 2014; NIST, 2014, 2012, 2010; European Commission, 2013; TESSY, 2008).

It is accepted that not all standards are developed through formal standardisation processes (Wang and Kim, 2007; Allen and Sriram, 2000; Tassey, 2000; Metcalfe and Miles, 1994; US International Trade Commission, 1990). However, attempts to anticipate the standardisation needs of emerging technologies is, of course, challenging. This is partly because of the non-linear, highly complex, and highly uncertain nature of innovation. It is also because standardisation processes are complex and dynamic,

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involving: high levels of technical detail and consensus; various types of standards in terms of both their role and the developing organisations; different motivations and requirements from stakeholders; and the integration of information relevant for standards development which is distributed among a variety of innovation system actors (Blind et al., 2010; Swann, 2010; Wang and Kim, 2007; Sherif, 2001; Allen and Sriram, 2000; Tassey, 2000). Furthermore, given this complexity, there is significant potential for competing standards visions or premature consensus to emerge, leading to ineffective or even counterproductive standards (Swann, 2010; Tassey, 2000; Foray, 1998).

Given these opportunities to support innovation and enhance technology strategies, and the related difficulties, there is an increasing awareness of the importance of developing robust frameworks and processes for anticipating standards more effectively (Heseltine, 2012; European Commission, 2011; NSTC, 2011b;). In particular, there is recognition of the potential value of new foresight approaches which could more clearly link opportunities for standardisation to specific innovation activities and the R&D needs of emerging technologies (Scapolo et al., 2014, European Commission, 2011).

This paper proposes a structured approach, grounded in technology roadmapping, for exploring the potential standardisation needs of emerging technologies. The proposed framework for the approach, which emerged from a series of systematic studies conducted for the British Standards Institute and the UK Department of Business, Innovation and Skills (Featherston et al., 2014; Ho and O'Sullivan, 2013; Brévignon-Dodin and O'Sullivan, 2013; O'Sullivan and Brévignon-Dodin, 2012), highlights important factors that need to be accounted for when developing standardisation strategies. These include: (a) important categories of innovation activities which may require supporting standardisation; (b) different categories or types of standards (i.e. codifying different types of technical knowledge); (c) the diverse and evolving sets of stakeholders involved in standards development processes; and (d) the timing and sequencing of standards development (and revisions).

The principles of the framework are demonstrated using recent 'historical examples' of standards development for three important but contrasting emerging technologies: synthetic biology, additive manufacturing, and smart grid. The case studies suggest that the innovation-theme and time-based structuring of innovation activities provided by the established technology roadmapping framework can be leveraged to support the anticipation of standardisation needs and opportunities.

2. Conceptual foundations

2.1. Standards and their contribution to innovation

Although there are variations in how the term 'standard' is defined, the following key common elements are included in multiple definitions by scholars and practitioners: established by consensus; approved by a recognised body; provide 'rules, guidelines, or characteristics for activities or their results'; 'aimed at the achievement of order'; and coherence in technical or commercial activities, particularly to ensure that users have confidence that codified knowledge, materials, products, processes, and services, among others, are 'fit for purpose' (Ho and O'Sullivan, 2014, Hatto, 2010 p. 5; Blind and Gauch, 2009; BSI, 2006; ISO, 2004; Allen and Sriram, 2000). Standardisation is the pursuit of these through conformity, has a number of motivations, and is driven by a variety of innovation actors (Tassey, 2000; Metcalfe and Miles, 1994, p. 588). The key difference between a standard and standardisation is that standardisation often occurs, at least to a certain extent, and is sometimes inevitable, whether a standard is acknowledged or formally established or not.

Standards (and standardisation) may have both positive and negative impacts on innovation (Swann, 2000; Tassey, 2000). Despite their potential to constrain certain innovation activities, carefully constructed and implemented standards can create an infrastructure that supports transferring innovative ideas, hence facilitating innovation.

There is a long tradition of academic work (e.g., Brady, 1933) exploring the potential for standards to obstruct innovation by limiting technological variety. Hanseth et al. (1996), p. 408, for example, argue that standards 'increase irreversibility and decreases interpretative flexibility of the technologies'. Standards may result in problems of lock-in to inferior standards or the risks of monopoly, which are potentially detrimental to innovation (Swann, 2000). For example, health and safety standards for consumer protection may lead to firms focusing on fewer innovative technologies, which, in turn, results in reduced consumer choice (BERR, 2008). As Foray (1998), p. 81 puts it, there are two apparently contradictory logics 'that of freedom, creativity and dynamics related to innovation and that of stability, order and routine associated with standards'.

Recently, there is a growing understanding that standards, more generally, play critical roles in supporting various innovation activities. For example, in a bibliometric analysis, Choi et al. (2011) demonstrate that well-designed standards support various innovation activities. A number of recent studies support these findings and suggest standardisation performs important functions in support of innovation. They include: defining and establishing common foundations upon which innovative technology may be developed (NSTC, 2011a); codifying and diffusing state of the art technology and best practice (Tassey, 2000), making them available as a basis for further innovation (Hatto 2010; Swann 2010; Allen and Sriram 2000); and allowing interoperability between and across products and systems, stimulating the diffusion and integration of new technologies into (product and service) systems (Blind and Gauch, 2009; Tassey, 2000).

Of particular interest in the context of this paper is the 'mediating' function of standards – diffusing new knowledge between innovation actors. This function has been highlighted in a number of academic publications (Blind and Gauch, 2009; Allen and Sriram, 2000; Tassey, 2000) and publications from practice (European Commission, 2011; Express, 2010). The European Commission (2011, p. 6) identifies standards as highly effective mechanisms for knowledge transfer, helping 'to bridge the gap between research and marketable products or services'. The Expert Panel for the Review of the European Standardisation System (EXPRESS, 2010, p. 16) also notes that 'standardisation converts new knowledge from scientific research into market' through various types of standards. In addition, Blind and Gauch (2009) identify a variety of standards with different roles and how they support knowledge diffusion between and across various stages of innovation, including: terminology standards and measurement standards helping transfer knowledge from basic to applied research; interface standards facilitating the gap between applied research and experimental development of new products and processes; and variety reduction standards fostering diffusion of knowledge in new products. Structured frameworks drawing on these distinctions could help better reveal standardisation needs and where standards might support innovation by matching these needs to particular standards based on the specific roles and functions they perform.

2.2. Frameworks for understanding technological innovation (and supporting technology strategy development)

To better reveal standardisation needs, the innovation process itself needs to be characterised in more detail. This section briefly discusses frameworks for understanding technological innovation and structuring technology foresight, and how they have been configured to anticipate standards.

A number of conceptual frameworks have been developed to better understand the systems and processes involved in the innovation and development of emerging technologies (e.g. Tassey, 2005; 2007; Geels, 2002; Utterback, 1994; Van de Ven, 1993b; Sahal, 1985; Dosi, 1982). Such frameworks pay particular attention to distinctions between different types of technologies, stages of development (lifecycle), innovation system activities, and the institutions that support innovation. Like the standardisation literature, the innovation systems literature also acknowledges the functions standards can play in innovation, such as legitimising new technologies and diffusing knowledge and know-how that are critical for the innovation process itself (Swann, 2010; Bergek et al., 2008; Ehrnberg and Jacobsson, 1997; Lundvall, 1992).

There is also a complementary strand of literature on strategic frameworks designed to support the development of technology foresight or planning (Phaal et al., 2010; Popper, 2008; Kostoff and Schaller, 2001; Garcia and Bray, 1997). Foresight frameworks, such as technology roadmapping, are typically quite flexible and scalable and their architectures are readily reconfigurable to include key categories of innovation activities relevant to the foresight topic (Lee and Park, 2005; Phaal et al., 2004). Nevertheless, there has been limited exploration of how particular frameworks for such foresight analysis (e.g. technology roadmapping architectures) might be used to facilitate more effective identification and timely anticipation of important opportunities for standardisation. Although there have been a few scholarly attempts to establish frameworks that explore the evolving and varied roles of standards in technological innovation and development (e.g., Blind and Gauch, 2009; Sherif, 2001; Tassey, 2000), none of these frameworks effectively capture all factors that are essential in identifying standardisation needs.

Due to this gap in foresight research and practices, standards are typically not addressed in significant detail in recent governmental technology strategies and roadmaps (e.g., TSB, 2012; HLG KET, 2011; BMBF, 2010). There is especially limited exploration of standardisation needs at the earlier stages of pre-competitive development as technologies emerge from the research base. This is despite the European Commission and other national governments calling for researchers to be provided support so they can engage more actively in standards development earlier in the innovation process (Heseltine, 2012; European Commission, 2011).

To inform the design of a framework for anticipating standards needs for emerging technologies, the key characteristics of standards and their development challenges need to be understood. The remainder of Section 2 is dedicated to drawing out these characteristics and challenges.

2.3. *Characterising standards and standardisation*

Standards can be classified or categorised in a number of different ways. A common way of distinguishing between standards is their *de facto* or *de jure* status (see ANSI, 2014; Hatto, 2010; Wang and Kim, 2007; Allen and Sriram, 2000). Other means of classifying standards are by the expertise and focus of the standards development organisation (SDO) leading the standards development process and the types of technical knowledge and information the standards are designed to codify and disseminate. These last two are discussed in more detail in the following sections.

2.3.1. *Different standards development organisations, with different expertise and focus*

Standards are sometimes differentiated by the different expertise and focus of SDOs leading the standards development process. Formal consensus standards are published by technical committees of national standards bodies (e.g., BSI, DIN, and AFNOR), multinational standards bodies (e.g., CEN, CENELEC, and ETSI), or international standards bodies (e.g., ISO, IEC, and ITU), whereas informal standards are generally published by private non-profit (industry-driven) SDOs (e.g., ASTM) (Hatto, 2010). Private standards are also developed by companies or trade associations. In addition, there are other important organisations involved in standards development, especially in the context of this paper's exploration of emerging technologies, including: professional engineering or scientific associations (e.g., IEEE, VDI, and IET), working groups of international consortia (e.g., W3C, OMG, and IETF) and research consortiums/research initiatives (e.g., BioBricks) (O'Sullivan and Brévignon-Dodin, 2012). Different organisations leading standards development often have different standardisation missions, contributions, and participation. Variations in the stakeholders involved in the standardisation process, and how these vary over time, are discussed further in Section 2.4.2 below.

2.3.2. *Different categories of standard: characterised by type of technical knowledge codified*

Of particular importance in the context of this paper – given its focus on strategy development for emerging technologies – are the categories of standards distinguished by the different types of technical knowledge they codify. These include:

- Terminology and semantic reference standards, which define common language and definitions to facilitate efficient communication among various stakeholders (Blind and Gauch, 2009; BERR, 2008).
- Measurement and characterisation standards, which specify methods for describing, quantifying, and evaluating product attributes for efficient R&D (Hatto, 2010; Blind and Gauch, 2009).
- Quality and reliability standards specify acceptable performance criteria along dimensions such as functional levels, efficiency, and health and safety (BERR, 2008; Tassey, 2000).
- Compatibility and interface (interoperability) standards, which specify properties that a technology must have in order to be compatible (physically or functionally) with other products, processes, or systems (Blind and Gauch, 2009; BERR, 2008).
- Configuration standards, which specify ranges, numbers, formats, architectures, or characteristics such as size or quality levels, to promote economies of scale and bolster users confidence and which can result in variety reduction (Hatto, 2010; Swann, 2010; Tassey, 2000).

This variety of standards, the variety of complex technical activities with potential for standardisation, and the large number of stakeholders involved in standards development, makes the comprehensive and systematic analysis of future standardisation needs of emerging technologies challenging. Any framework that attempts to systematically analyse future standardisation needs should also consider the evolving contribution of standardisation to emerging technologies and their implications for technology foresight.

2.4. *Standards and emerging technologies: the challenges for technology foresight*

Critical to any technology foresight analysis is its ability to explore, in sufficient technical detail, how different innovation activities, challenges, and opportunities may *evolve over time*. In the case of foresight efforts to anticipate the standardisation needs of emerging technologies, careful and systematic attention needs to be paid to: different standardisation requirements at different stages of emerging technology development (including standards for generic technologies and infrastructure); the evolving composition and motivations of stakeholders over time; and the implications of timing (i.e. sequencing) of different standards for other innovation activities and standardisation efforts.

There have been some efforts to carry out such analyses in practice, with varying emphases and approaches. For instance, an initiative launched in 2010 by the National Institute of Standards and Technology (NIST) in the US aimed to coordinate the development of standards for smart grid, acknowledging standards-related opportunities and challenges within a broad technology roadmap (NIST, 2014, 2012, 2010). The NIST initiative allowed the identification of relevant standards in the technological domain while pointing to priority gaps and harmonisation issues (NIST, 2010). It also provided a conceptual framework for depicting the different stakeholders involved in smart grid and how they interact with each other. In addition, it paid special attention to the actors involved in standards development, highlighting instances where coordination between Federal agencies and industry groups is required.

The EU *Towards a European Strategy in Synthetic Biology* (TESSY) project offers another example of an attempt to consider standards development in a strategic way (TESSY, 2008). Concerned with developing a vision for synthetic biology and assisting in shaping innovation policy, the TESSY roadmap pays special attention to timing- and sequencing-related issues and identifies four consecutive standardisation phases as part of a broader regulation dimension.

SASAM's (2014) additive manufacturing standardisation roadmap focuses on the timing of standards and classifies them with respect to process/product, materials, and productivity. However, the specific role of the standards and to which innovation activities they relate is not clearly outlined. Additional insights can be provided by the US *Roadmap for Additive Manufacturing*, which was published in 2009 (Bourell et al., 2009). Its overarching objective was to articulate a vision for research in the domain of additive manufacturing and identify priority R&D areas with high potential. Although it did not solely focus on standards, its systematic approach brought clarity on identifying standards-related needs and to the involvement of the additive manufacturing community in standards development (Bourell et al., 2014).

The above exercises demonstrate the value of a number of different considerations when anticipating standardisation needs, including: evolving standardisation requirements, the evolving composition and motivations of stakeholders, and the timing and sequencing of standards. However, none of the studies fully and systematically address all these considerations. The following sections discuss these considerations and dimensions in more detail and why they should be accounted for in foresight exercises that aim to anticipate the standardisation needs of emerging technologies.

2.4.1. *Evolution of standardisation requirements at different stages of technology development*

Standards perform various functions at different stages of technology development, and a number of scholars have identified that there are evolving levels of emphases on different types of standards at different phases in the emergence of a new technology. Blind and Gauch (2009) argue that as research and innovation progress, various types of standards are needed, playing different roles at different phases of the innovation journey. Tassey (2000) has also developed a framework representing how various types of standards with different roles are required throughout the various stages of innovation and industrial activities for efficient development and utilisation of technology. In addition, Sherif (2001) has proposed a framework relating different types of standards with various stages of a technology's lifecycle, from anticipatory standards developed at the introduction of the technology, to participatory standards adopted when the performance improves, followed by responsive standards developed as technology matures. This timing relationship between standards and technology lifecycles is essential, with 'different degrees of standardisation… [being] optimal at different points in the technology's… evolution' (Sherif, 2001; Tassey, 2000, p. 601). With such conceptual backgrounds, Ho and O'Sullivan (2013) provide empirical evidence which suggests that different types of standards emerge at different stages of technological innovation and development, using the case of photovoltaic technology. Due to the time-dependent characteristics of standards and their dual nature (limiting and supporting innovation activities), the timely and appropriate development of standards is critical for effective support of innovation.

2.4.2. *Evolving composition of standards development stakeholders*

The academic literature on standards and innovation has also stressed the importance of involving innovation stakeholders in standardisation activities and exploring the ways in which their engagement can affect the standards development. For instance, Yoo et al. (2005) consider successful innovation as a collective achievement made possible only by a network of actors from industry, finance, research, and government whose interests are mediated through standards. Mapping out the standardisation landscape for nanotechnology, Blind and Gauch (2008) highlighted the large number of stakeholders interested in standards development and the importance of their participation at certain stages of the innovation process. These stakeholders include: the German standards development organisation (DIN); the German Commission for electrical, electronic, and information technologies (DKE); companies; and research organisations, including universities and privately and publicly funded research organisations (including government laboratories).

Public intervention and the roles of government in standardisation activities have also been reported in various publications, drawing the attention of both academics and practitioners. At a theoretical level, Edquist (1999) viewed technical standards as non-market mechanisms that governments could use to foster innovation in technology specific domains. Based on a case study of information technology standards in South Korea, Wang and Kim (2007) explored the conditions under which the government got involved in standardisation activities. Furthermore, NIST (2011) identifies a number of practical modes through which public actors engage in standards development in the US, including convenor/coordinator, technical leader, participant, facilitator, implementer, funder, technical advisor, and coordinator of Federal Agency needs.

In addition to the variety of stakeholders and their different modes of engagement, stakeholders play different roles at different stages of the innovation process, implying that their involvement in the development of standards will also change as a technology develops. Furthermore, this suggests that possible sources of funding for standardisation activities from those, public and private, interested in seeing it occur will similarly change. Therefore, there is considerable value in identifying these sources of funding for more effective and strategic management of standardisation activities. Despite this value, the composition and timing of stakeholder involvement tend to be overlooked in policy initiatives that aim to support innovation through the strategic development of standards.

2.4.3. *Timing and sequencing of different standards*

As well as the coordination of standardisation activities relative to various stages of technological innovation, standards also need to be coordinated relative to other standards, particularly as standardisation strategies often involve the development of more than one standard (e.g., SASAM, 2014). Tassey (2000) argues that as standards are a complicated system that influence each other, there is potential for competing standards to emerge, resulting in inefficient or even counterproductive standardisation system. Gandal (1995), through a study of the PC software market, also demonstrates that competing standards can create negative network externalities. The coordination, alignment, and sequencing of standards relative to each other are thus important considerations for a systematic and comprehensive analysis of standard needs and opportunities for emerging technologies.

In summary, an effective foresight framework for exploring the standardisation requirements of emerging technologies needs to account for the following critical strategic considerations and dimensions in appropriate detail:

- *Time* – Should be the underpinning principle, enabling the framework to reveal the dynamics of innovation and standardisation activities, including sequencing, interdependence, and the changing composition of stakeholders.
- *Technological innovation activities* **–** Should be identified in appropriate detail to reveal: opportunities for standardisation, where relevant knowledge needs to be transferred, and where user requirements might be defined.
- *Standards types* **–** Should be identified in a comprehensive way to ensure that standards are developed in a form that is effective for knowledge transfer and diffusion.
- *SDOs and participants* – Should be identified for strategic coordination among stakeholders involved in standardisation activities.

One of the most widely used foresight approaches for developing emerging technology strategies is technology roadmapping (e.g., TSB, 2012; NASA, 2010; Bourell et al., 2009). The fundamental elements of the technology roadmapping framework incorporates the first two considerations and dimensions listed above, namely a time dimension and a structured, systematic way of characterising innovation activities (Phaal et al., 2010, 2004; Phaal and Muller, 2009). Technology roadmapping also lends itself to being adapted to consider the remaining two considerations and dimensions: standards types and SDOs and participants.

The following section contains an introduction to technology roadmapping, followed by a discussion of how it was adapted to become the proposed framework for exploring the standardisation needs and opportunities of emerging technologies.

3. Principles for the development of a standards mapping framework

3.1. Technology roadmapping

A technology roadmap provides a coherent and holistic view or vision of future technology landscapes and systems, identifying the critical system requirements, the performance targets, and the technology alternatives and milestones for meeting those targets (Phaal and Muller, 2009; Kostoff and Schaller, 2001; Garcia and Bray, 1997).

The technology roadmapping process brings together a team of experts to not only collect, organise, and present the critical information they anticipate will be needed for technology development, but also identify, select, and develop strategic alternatives for desired objectives (Kostoff and Schaller, 2001; Garcia and Bray, 1997). It is a process that contributes to the definition of technology strategy by bringing consensus and creating a common vision among various stakeholders (Amer and Daim, 2010; Popper, 2008; Groenveld, 2007, 1997); this is similar to the process of developing standards, suggesting the potential of the roadmapping framework for informing standardisation strategy development.

A technology roadmap can take a variety of forms. The fundamental technology roadmapping framework adopted here is described by Groenveld (2007, 1997), Phaal et al. (2010, 2009, 2004), and Phaal and Muller (2009). This framework has a clear time-based strategic planning format and, typically, a graphical representation of innovation activities which facilitates awareness of interdependencies and sequencing issues (Phaal et al., 2010, 2009, 2004; Blackwell et al., 2008). The framework is time-based (horizontal 'axis') with multiple themes (e.g., functions and disciplines) representing key categories of innovation activities necessary to understand and depict the overall innovation system. Three broad thematic questions relevant to any strategy – how, what, and why – align with Groenveld's (2007, 1997) market, product, and technology-R&D project categories respectively and have been stacked similarly by Phaal et al. (2004) bottom, middle, and top respectively. The time dimension allows these to be mapped in terms of stakeholders' visions and objectives, and the framework as a whole helps map different stakeholder's perspectives and draws out the relationships between those perspectives (Phaal et al., 2009). Such a generic technology roadmap is able to provide a *systematic* view of complex, dynamic systems, enabling 'the evolution of a complex system to be explored and mapped, supporting innovation and strategy development' (Phaal et al., 2009, p. 287). In particular, the roadmap 'layers' (themes) are configured to correspond to the important categories of technological innovation activity which are used to explore key innovation activities (Phaal et al., 2004), their barriers and enablers (Phaal et al., 2004), as well as technology-push and demand-pull drivers of emerging technology innovation (Phaal and Muller, 2009). Technology roadmapping has been adopted in many private (e.g., Jereza et al., 2005; Cisco Systems, 2003; IBM, 2002; Silverman, 2002) and public (e.g., TSB, 2012; NASA, 2010; Bourell et al., 2009) technology-planning exercises, at least partly for its ability to help understand the innovation activities and contextual factors involved in innovation. This offers context for exploring where standards could be used to support or mediate between these innovation activities.

3.2. The standards mapping framework

We use the above technology roadmapping concepts to develop a framework aimed at identifying standardisation opportunities in emerging technologies (an illustration of the framework can be seen in Fig. 1). Typically, when attention is paid to standardisation in emerging technology roadmaps, standards have usually been incorporated as a single category of innovation 'enabler' (Phaal et al., 2010, 2011; Phaal and Muller, 2009; e.g., TSB, 2012). However, as stressed by the literature review in Section 2, different standards interact with different innovation activities and support the diffusion of different categories of information and knowledge between these activities. In order to more adequately reflect the detail and the diversity of roles standards have in emerging technology development, the framework proposed in this article (depicted in Fig. 1) distinguishes different standards types (based on the knowledge they codify) and enables these standards to be linked to the innovation activities affected. Linking lines are often used as a roadmapping convention to indicate interdependent innovation activities and activity sequences. Where standards help mediate between these activities, a circle with an S symbol is placed on the line. Arrows in two directions indicate the 'mediating' function of standards – where they transfer knowledge

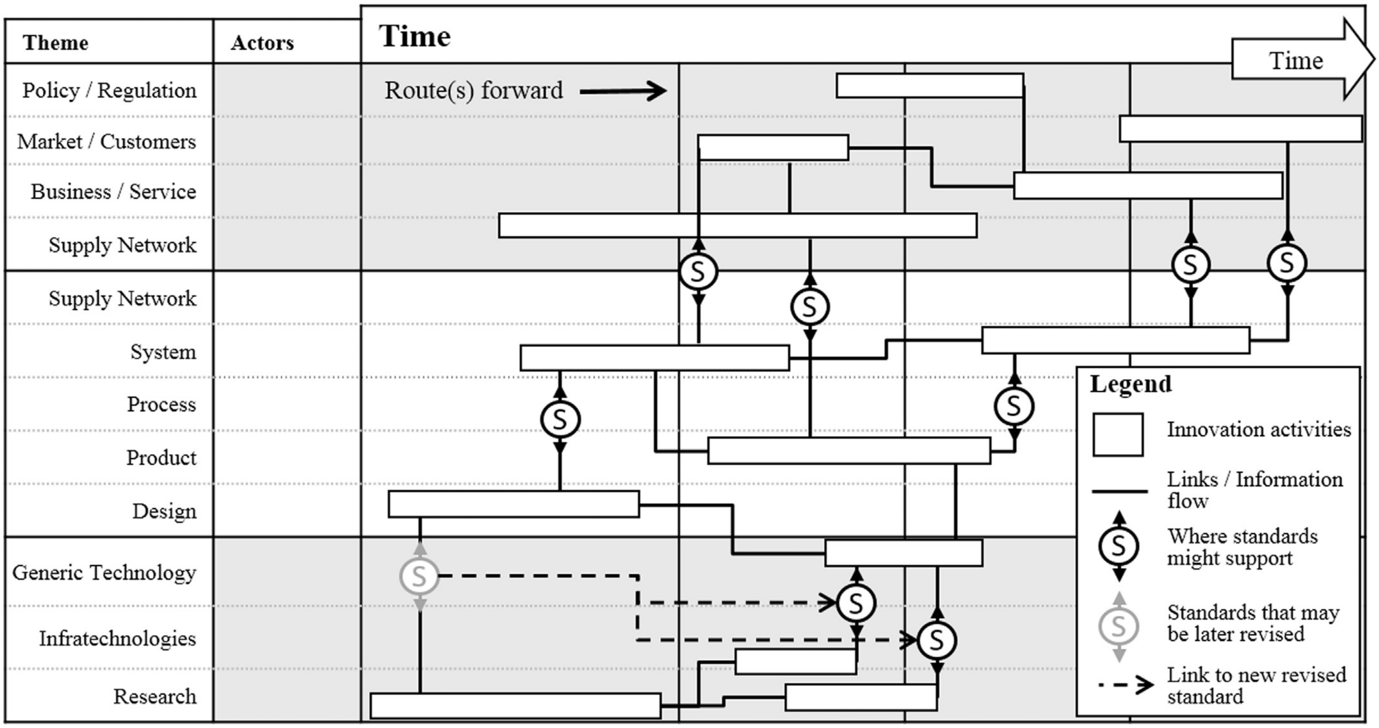

Fig. 1. Standards mapping framework, highlighting important categories of innovation activities (based on Phaal and Muller (2009)). NB: *Supply network* is depicted twice because of its dual internal- and external-nature.

and information between and across various stages of innovation, as Blind and Gauch (2009) suggest. Potential stakeholders are also identified through the actors directly involved in the linked activities. It also allows us to observe complex dynamics between standardisation and other innovation activities occurring within the various themes of the general roadmapping framework over time.

The vertical axis of the framework (Fig. 1) is structured in the same three broad categories as suggested by Groenveld (2007, 1997) and Phaal et al. (2004). The themes are adopted directly from Phaal et al. (2010) and Phaal and Muller (2009), and can be customised to accommodate particular characteristics of the technology or technical domain in question. The policy and regulation perspectives have been added because such political and legal aspects play critical roles in standardisation activities and because governments and regulators are key stakeholders in developing standardisation strategies. The bottom section of the framework has been further refined using generic technology – the technological stock that is configured and reconfigured by industry to create proprietary technologies and is replenished from the research base (Tassey, 2007, 2005; Keenan, 2003). Also included are 'infratechnologies' – which support technology development and integration by providing capabilities such as modelling, characterisation, testing, and measurement (Tassey, 2007, 2005). Generic technologies and infratechnologies are included not only because they help to characterise innovation more precisely and because they may be an important innovation enabler (Tassey, 2005, 2007), but also because they may require standardisation themselves or may be necessary technical bases for standards (Tassey, 2000).

The framework is proposed as a means of capturing the critical considerations and dimensions needed to explore the standardisation needs of emerging technologies drawn out in Section 2. It uses the underpinning technology roadmapping framework to elucidate individual innovation activities and, by mapping them over time, their sequences and interdependencies. This provides a canvas for identifying where standards can help diffuse information, informed by the various types of standards that can be employed. The participants involved in the standardisation activities can then be identified based on those involved in the relevant innovation activities and the information being diffused.

Similar to the technology roadmapping framework, the proposed framework can be adapted to suit a range of situations. For example, grey standards have been added to the depiction of the framework in Fig. 1 to indicate standards that have been or will be withdrawn or revised and have been linked to their revised versions by a dotted line with an arrow. This helps to more completely depict the 'system' of standards relevant for an emerging technology.

Essentially, the framework is designed to map various types of standards with different roles and functions, according to relevant dimensions of emerging technology innovation activities and across the stages of the innovation journey. Further, it supports the better articulation and visualisation of how standards-related activities can support the overall innovation system by helping to identify future standards needs to facilitate knowledge diffusion and highlighting any potential coordination, alignment, and sequencing issues related to standardisation activities.

4. Case studies

The framework is applied in three case studies in three different technology domains – synthetic biology (SB), additive manufacturing (AM), and smart grid (SG) – to demonstrate its underlying principles. These domains have been selected because of their contrasting characteristics: they are technologies that are fundamentally different in nature (i.e. a platform technology, a production technology, and a system of technologies), at different stages of maturity (i.e. a scientific field being converted to an engineering discipline, an engineering application being informed by scientific discovery, and an existing system with new science and

Table 1
Standards observed in the synthetic biology case study, selected for their variety and varying levels of interdependence.

Standard (chronological order)	Simplified title	Role	Developer
BBF RFC 8	Early standard design for biological parts	Physical configuration	BBF
BBF RFC 11	Assembly methods	Physical configuration	BBF
BBF RFC 18	Conceptual guidelines in support of graphical language	Data exchange	BBF
BBF RFC 19	Measurement of activity of promoters	Measurement	BBF
BBF RFC 23	Assembly methods for protein engineering	Physical configuration	BBF
BBF RFC 30	Framework for the exchange and integration of data v.1	Data exchange	BBF
BBF RFC 32	Framework for the exchange and integration of data v.2	Data exchange	BBF
BBF RFC 37	Assembly methods in support of protein fusion	Physical configuration	BBF
BBF RFC 41	Promoter measurement units	Measurement	BBF
BBF RFC 48	Automated design of biological circuits	Functional composition	BBF
BBF RFC 57	New assembly method	Physical configuration	BBF
BBF RFC 59	Quantitative measurement method using flow cytometry	Measurement	BBF
BBF RFC 69	Interconnection of parts	Physical configuration	BBF
BBF RFC 84	Synthetic Biology Open Language (SBOL) v.1	Data exchange	BBF
BBF RFC 87	Synthetic Biology Open Language (SBOL) v.2	Data exchange	BBF
BBF RFC 93	Synthetic Biology Open Language Visual (SBOL Visual)	Data exchange	BBF

engineering sub-systems continually being integrated into it), with different actors involved in their development, and with different knowledge structures. Furthermore, standards in the three fields have been developed by different sources and are often developed differently. These case studies build on a series of systematic reviews of emerging technology strategies, standardisation efforts in relation to these strategies, and how standardisation has occurred during their development (Featherston et al., 2014; Brévignon-Dodin and O'Sullivan, 2013; Ho and O'Sullivan, 2013; O'Sullivan and Brévignon-Dodin, 2012).

The case studies use historical examples to demonstrate the principles, and provide representative, illustrative examples, of the framework. They depict how potential standardisation needs might be identified based on the knowledge diffusion needs of innovation activities. The case studies use the development and adoption of standards as a proxy for standardisation needs. It was found in the case studies that standards diffuse information between a number of similar activities and as a result these activities have been clustered into broader *aggregate* activities. The consequence for the case studies (and the implications for the framework) is that they depict standardisation opportunities based on the diffusion needs between clusters of innovation activities.

In each case study a small selection of standards are explained in detail to illustrate the information they codify and the functions they perform. Demonstrating the principles of the framework in these three domains provides examples of the framework's ability to capture the aforementioned considerations and dimensions that are relevant for understanding the standardisation needs in emerging technologies (see Section 2.4) and the diversity of studies demonstrates the framework's flexibility and adaptability.

While the additive manufacturing case study includes all formal standards developed specifically for additive manufacturing, too many standards have been developed for synthetic biology and smart grid to depict them all in the studies. Instead, a selection of standards was made in these domains to demonstrate the framework's ability to identify standardisation needs that require various types of standards to be developed by a variety of sources.

It should be noted that the representative, illustrative examples shown in the case studies depict only the innovation activities and links related to the selected standards to make the mapping manageable. While this neglected several activities and links, it should be remembered that these case studies are a demonstration of the concepts reflected in the framework. The arrows on the links, which are often used to indicate information flow, are also reflected only in the standards symbol itself for visual simplification.

4.1. Synthetic biology

Synthetic biology is a rapidly emerging area of biological research. It is concerned with 'the redesign and engineering of biological systems and processes for new uses' by taking 'naturally occurring genes and engineer[ing] new genes and hence [new] organisms' (Willetts, 2013, p. 32). The technology is at an early but rapidly developing stage, with potential applications in a vast number of sectors, such as healthcare, energy, environment, chemicals, and materials.

Spanning traditional microbiology to some more (biologically-based) engineering disciplines, biology intrinsically requires standardisation (Torrance and Kahl, 2012; Endy, 2005). Decoupling biological design from fabrication, in particular, has led to abstraction- and standardisation- related needs to manage biological complexity (NAKFI, 2010). Interest in standardisation activities has therefore been an ongoing concern of the synthetic biology community, with researchers getting proactively engaged in standardisation activities (Torrance and Kahl, 2012; Keasling, 2005).

Special attention is being paid to standards related to the definition and characterisation of parts, data sharing, and measurement because synthetic biology is still at an early stage of development. The relative immaturity of the field is reflected in the technical standards framework launched by the BioBricks Foundation (BBF). Proposing a catalogue of 104 standards, BBF focuses on those standards associated with early stage research activities like the description of parts, devices and systems; data capture and exchange; and assembly and measurement tools. This catalogue has been used as the reference database to conduct this case study as it is well established and used by synthetic biology researchers. These standards can be considered as 'community-building standards' because they aim to bring cohesion to the variety of stakeholders conducting different research and contributing to the field in a variety of ways.

The BBF standards in Table 1 were selected from the catalogue to represent four roles performed by the standards developed by the BBF community in support of synthetic biology. The roles, and associated types, include physical configuration standards for the physical assembly of individual biological components into larger and multi-component systems; functional configuration standards to inform biological part assembly so they function in a predictable way; and reference standards in support of measurements and data exchange for the electronic exchange of information on genetic parts and systems (Torrance and Kahl, 2012). A test for the framework was to capture and reflect the roles of these standards with respect to relevant innovation activities. Unfortunately the BBF catalogue only provides some dates for the standards, some

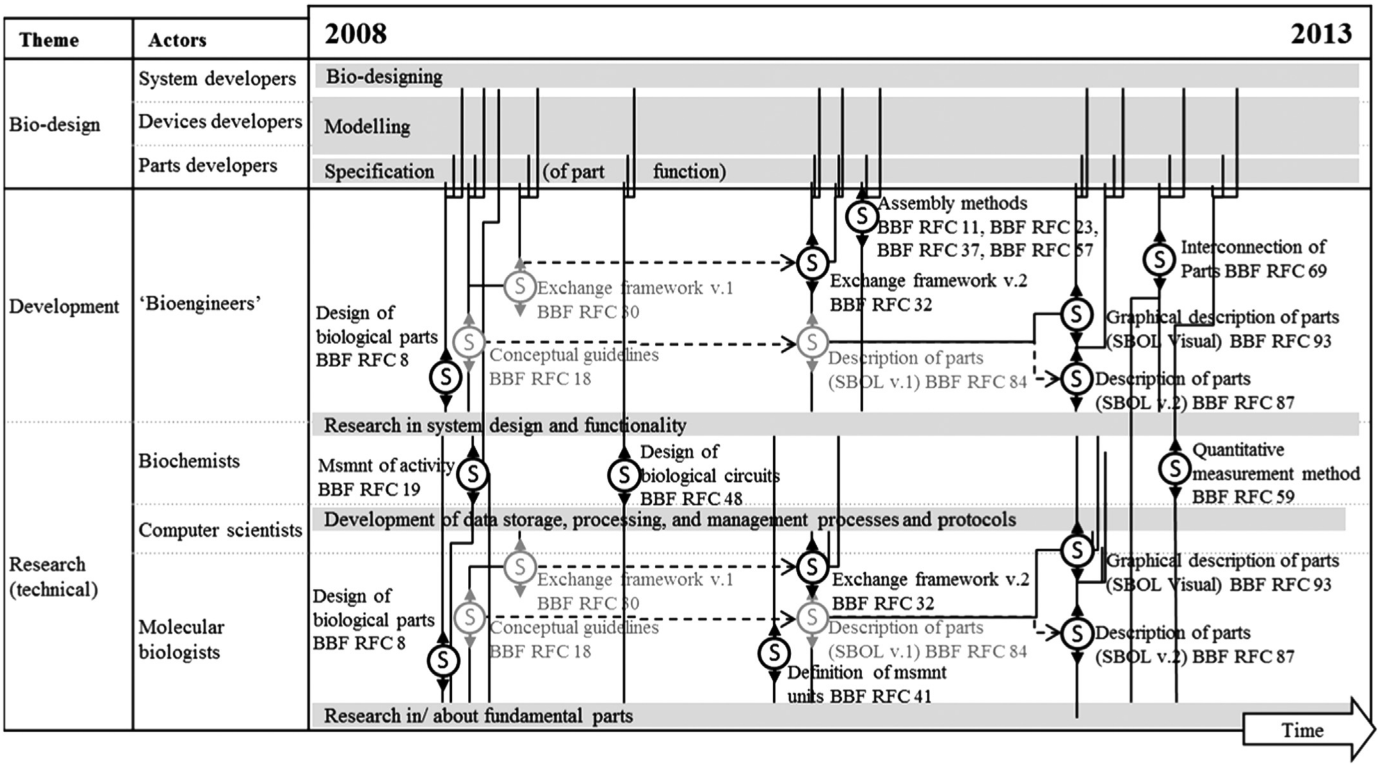

Fig. 2. Illustrative example of the framework for synthetic biology. NB: to simplify the diagram visually, some standards have been duplicated.

relating to submission dates and some to the date they were accepted. As a consequence Table 1 shows only the relative chronology of the standards.

Fig. 2 is a representative illustration example of the standards shown in Table 1 mapped using the principles of the proposed framework. As can be seen, the innovation activities focus predominantly on research, reflecting synthetic biology's early stage of development. The links in Fig. 2 indicate where standards have been developed to support the codification and transmission of knowledge between particular (aggregated) innovation activities.

The fundamental nature of BBF's description of synthetic biological systems – which defines parts, devices, the ways they interact with each other, and the ways they interact within an overall system – means that standards relating to these distinctions are relevant for almost all research activities. The BBF deemed these terminological and semantic distinctions so important that specific standards needed to be developed to diffuse this information (i.e. BBF RFC 87 and BBF RFC 93). Fig. 2 indicates that the proposed framework is potentially capable of drawing out fundamental and pervasive standardisation needs such as terminology and semantics (*Terminology and semantic reference standards*, see Section 2.3) through the identification of different research and development activities and their communication and information diffusion needs.

Many of the standards reflected in Fig. 2 (e.g., BBF RFC 19 and BBF RFC 48) also indicate the need for the characterisation and measurement of biological parts to support information transmission from innovation activities in the research base to activities related to the further development of circuits. Again Fig. 2 indicates that such standardisation needs can be captured and reflected by the framework because of its attention to carefully characterising innovation activities and their knowledge needs.

Fig. 2 also illustrates the approach used to identify different types of stakeholders that standards are diffusing information between, based on their involvement in the related innovation activities. The stakeholders identified in Fig. 2 include computer scientists, molecular biologists, and bio-designers.

In addition, it reflects the dynamic evolution of standards, which is exemplified by the update of SBOL (a data exchange standard for describing genetic parts and systems). This evolution of standards is presented against a general, relative timeline, with standards mapped relative to each other.

Fig. 2 also indicates that the proposed framework can be tailored to capture the standards-related characteristics of very early stage emerging technological domains, including those aimed at establishing and consolidating a new technology-based community, such as synthetic biology.

Finally, the mapping of the standards reveals the fundamental nature of standards developed at the earlier stages of technology development. The wide influence of the terminology and semantic standards in facilitating diffusion between innovation activities, the number of links between so few clusters of innovation activities, and the importance placed on measurement and characterisation standards for supporting the research-to-development transition indicate how important these standards are for developing technology further in an emerging field.

4.2. Additive manufacturing

The term additive manufacturing refers to a number of different technologies and contributes to a number of other manufacturing related capabilities. The technologies referred to by the term additive manufacturing include stereolithography (SL), selective laser sintering/melting (SLS/M), electron beam melting (EBM), inkjet (or binder jetting), fused deposition modelling (FDM), and laminated object manufacturing (LOM). It also includes a number of material-equipment configurations such as powder-bed infusion (a technique used in SLS, EBM, or inkjet) and material 'jetting' (used in SLS, EBM, and binder jetting). These technologies contribute to a number of manufacturing capabilities, including direct manufacturing, direct digital manufacturing, rapid manufacturing. The terms additive manufacturing and three-dimensional printing (3D printing or 3DP) are often considered different, the prior being about industrial application and the later about the maker-movement. Here we use the definitions as outlined in ASTM F2792, where 3DP is a technological subset of additive manufacturing

Additive manufacturing has a number of advantages over other manufacturing processes. It has the ability to create parts with unique geometries and other unique structural and functional properties, and create net- and near-net-shape parts. As a process it generally has low material wastage, scalability, some skills transferability due to digital design and input, versatility, and often reduced change-over costs and time. Additive manufacturing is used to manufacture a range of different products, including toys and trinkets, jewellery, aerospace components, and materials for medical applications, both for tissue production and the fabrication of bio-inert parts, such as prostheses. AM was selected because it covers a number of manufacturing technologies that are at different stages of maturity, based on the technology itself and what it is being used to manufacture. This provides contrasting standardisation priorities both within additive manufacturing and between additive manufacturing and the other case studies.

A number of standards have been developed by SDOs for additive manufacturing. For example, ASTM International (ASTM) has developed and is developing standards through the F42 committee, ISO through the Technical Committee 261 (ISO/TC 261), and the British Standards Institution (BSI) through the Advanced Manufacturing Technology Committee 8 (AMT/8 Additive manufacturing). These standards codify different information, have varying roles, and perform different functions. ASTM has classified its published standards relating to additive manufacturing into terminology, materials and processes, design, and test methods. ISO has classified its additive manufacturing related standards according to various categories in the International Classification for Standards (ICS). However, more specific intended roles and functions can be acquired from the description of the standards themselves. The published standards (to the end of 2014) and their interpreted roles can be seen in Table 2. The table excludes standards that might apply to additive manufacturing but were not developed specifically for additive manufacturing, such as health and safety standards and product data representation and exchange standards (such as ISO10303).

An illustrative example of the standards shown in Table 2 mapped onto the proposed framework is shown in Fig. 3. The only standard not depicted in Fig. 3 is terminology-focused standard, ASTM F2792 (2012). The standard contains generic definitions of terms used in the field and supports communication between and within all activities within the industry, not only innovation activities. Because of its pervasiveness it is not depicted here to make the illustrative example clearer and easier to follow (for an illustration of terminology standards, see the synthetic biology case study in Section 4.1). For similar reasons the Part characterisation and testing standard ISO/ASTM 52921 (2013), which includes some terminology, is only depicted in its primary function: to communicate part properties between producers and users.

A review of the standards developed for additive manufacturing indicated that they are designed to support communication between different stakeholders and different innovation activities. The mapping in Fig. 3 illustrates how standards can be depicted in this role. For example, BS/ISO 17296-4 (2014) was developed to standardise data exchange of requested 3D geometries between producers and users, including software engineers, manufacturers, part users, and test bodies. Specification of such information is an important role standards perform (Swann, 2010; Hatto, 2010; Tassey, 2000). This perspective of standards suggests that the links in maps like Fig. 3 are themselves a distinct 'diffusion' class of innovation activity, which sit apart from traditional roadmapping themes. It also suggests that such notions might be similarly

Table 2
Additive manufacturing standards developed by ASTM and ISO.

Standard	Date	Title	Role	Initial developer
ASTM F2792	2012	Standard terminology for additive manufacturing technologies	Terminology	ASTM
ISO/ASTM 52915	2013	Standard specification for Additive Manufacturing File Format (AMF) (v1.1)	Interoperability to support design	ASTM
ASTM F2971	2013	Standard practice for reporting data for test specimens prepared by additive manufacturing	Test methods and reporting procedures	ASTM
ISO/ASTM 52921	2013	Standard terminology for additive manufacturing-coordinate systems and test methodologies	Test methods and reporting procedures	ASTM
ASTM F2924	2014	Standard specification for additive manufacturing Titanium-6 Aluminum-4 Vanadium with powder bed fusion	Characterisation of materials and process	ASTM
ASTM F3001	2014	Standard specification for additive manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with powder bed fusion	Characterisation of materials and process	ASTM
ASTM F3049	2014	Standard guide for characterizing properties of metal powders used for additive manufacturing processes	Characterisation of materials and process	ASTM
ASTM F3055	2014	Standard specification for additive manufacturing Nickel Alloy (UNS N07718) with powder bed fusion	Characterisation of materials and process	ASTM
ASTM F3056	2014	Standard specification for additive manufacturing nickel alloy (UNS N06625) with powder bed fusion	Characterisation of materials and process	ASTM
ASTM F3091/F3091M	2014	Standard specification for powder bed fusion of plastic materials	Characterisation of materials and process and part/process specification	ASTM
BS/ISO 17296-3	2014	Additive manufacturing – rapid technologies (rapid prototyping) Part 3: test methods	Test methods and reporting procedures	ISO
BS/ISO 17296-4	2014	Additive manufacturing – rapid technologies (rapid prototyping) Part 4: data processing	Part specification (including requirements) and data processing	ISO

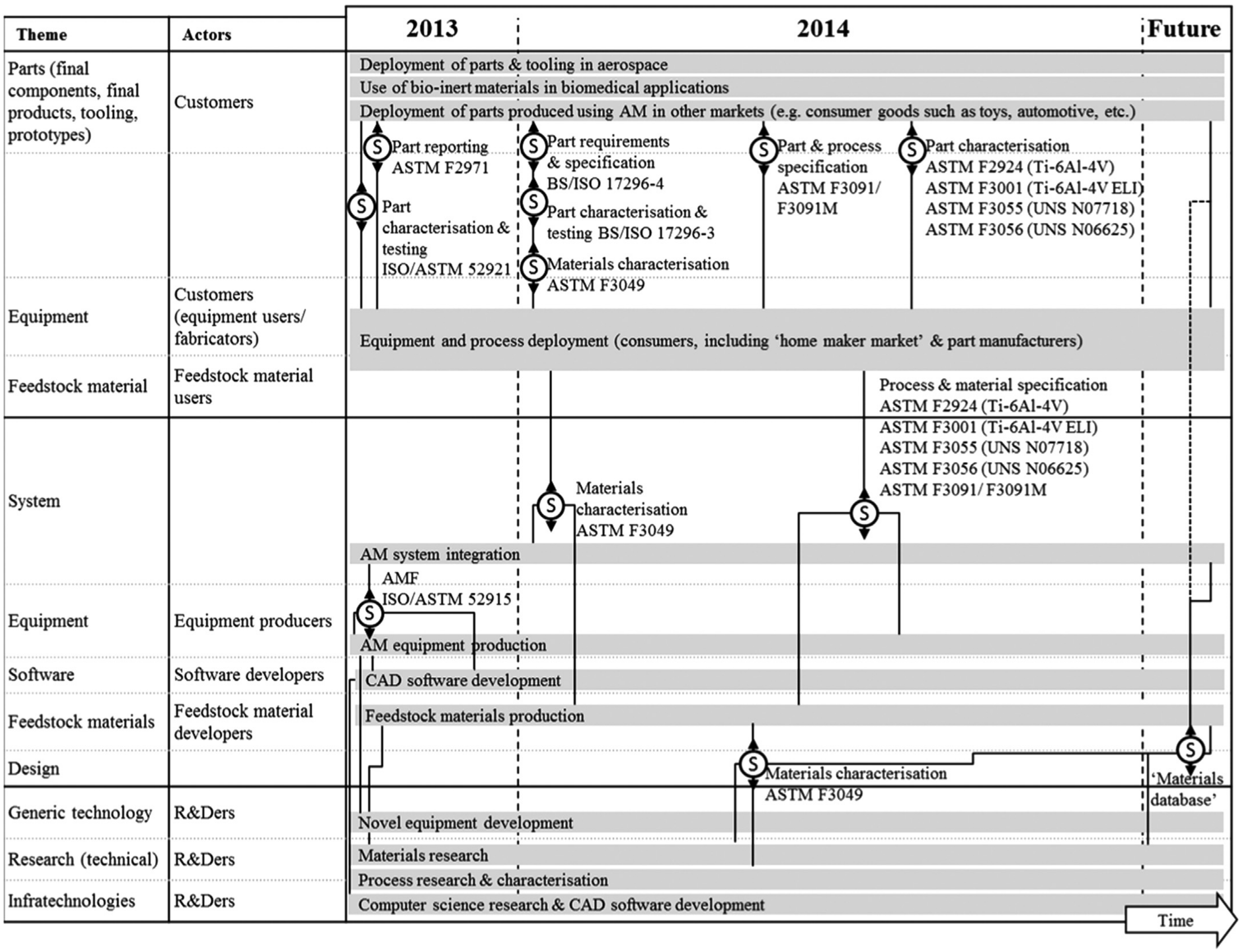

Fig. 3. Illustrative example of the framework for additive manufacturing.

applicable to other diffusion activities, such as workshops, conferences, and policy development exercises.

The mapping in Fig. 3 also reveals that standards (and even clusters of standards) support diffusion between clusters of innovation activities. This is why the innovation activities have been aggregated in Fig. 3. BS/ISO 17296-4 (2014) exemplifies this point and illustrates how a number of different stakeholders, engaging in a number of different but similar innovation activities, might use similar guidelines for codifying and transmitting information and knowledge.

Fig. 3 also indicates that the framework draws out the technical detail related to a technology, unlocking the ability to: identify relevant stakeholders; highlight where standardisation might support bilateral communication; and identify unique standardisation opportunities. First, Fig. 3 shows how the actors relevant to a standardisation effort, and potentially the development and deployment of a standard, can be identified through the characterisation of innovation activities and the stakeholders evolved in them.

Second, through the innovation activity actors, the mapping illustrates how the framework can highlight standards that support bi- or multi-lateral communication between actors. For example, BS/ISO 17296-4 (2014) supports the communication of part requirements to manufacturers and part characteristics to users and may also be used to mediate engagement with a third part. This has implications beyond the proposed framework, suggesting that standards not only perform a diffusion function but that they also mediate between the different actors involved in the innovation process.

Third, Fig. 3 demonstrates that because the framework helps to characterise the technical detail, it can highlight a variety of standardisation opportunities unrelated to application domains, but that are still relevant for a variety of different applications (i.e. application agnostic based on abstracted specifications of application). For example, it draws out application agnostic standardisation opportunities based on the general needs of innovation activities, such as characterising input materials (ASTM F3049, 2014), test methods (ISO 17296-3, 2014), and supporting software-equipment interoperability (ISO/ASTM 52915 2013). Furthermore, it highlights common combinations of materials and processes that can be employed in different applications, for example nickel alloy with powder bed infusion (ASTM F3055 2014). This advantage is particularly important for complex fields and is illustrated here by a field that draws on research from a variety of domains – including materials development, control systems, and software development – and recombines them in a range of computer-controlled manufacturing processes, which use different input materials, to create vastly different parts for a variety of applications.

Again, as in the synthetic biology case study (Section 4.1), the framework also captures standards as a bridging-medium between key innovation activity clusters (reflected in the aggregations of activities in Fig. 3). Many of the standards in the figure support communication between key developer and user groups, such as manufacturers, home-additive manufacturing equipment (3D printer) users, specialist manufacturing firms, and part and tooling users. This shows standards not only as key diffusion and mediation mechanisms, but also as legitimising mechanisms (see Swann, 2010; Bergek et al., 2008; Ehrnberg and Jacobsson, 1997; Lundvall, 1992), that can potentially enahance and provoke the expansion of innovative activity.

Finally, Fig. 3 also indicates how the framework can be used to anticipate standards that could be developed to support innovation. The timeline of published standards for additive manufacturing is quite condensed, with standards only having been developed between 2012 and 2014. However, the standard '*Materials database*' in Fig. 3, is an anticipated standard, which is not yet in development, but is based on the advocations of a number of industry personnel (e.g., Bryant et al., 2013; Liou, 2013). This standard would standardise a way of reporting the mechanical properties of materials produced using AM (perhaps using a database) and how they are to be compared to the same materials produced using traditional approaches; and would be designed to help diffuse this information and mediate between part users, part manufacturers, and feedstock material developers.

4.3. *Smart grid case study*

Smart grid refers to an advanced power grid for the next generation, integrating many varieties of Information and Communications Technology (ICT) and services with the existing power-delivery infrastructure. Bidirectional flows of energy and two-way communication and control capabilities will allow electricity from a diverse range of power plants (including renewable energy) to be delivered to consumers, not only improving power reliability, but also reducing carbon emissions and reliance on oil consumption. Smart grid was selected for the study because it is a system of technologies and provides different standardisation priorities to the other case studies.

The development of appropriate and readily available standards is critical in supporting interoperability between smart grid elements, integration of smart grid sub-systems, and the security of a smart grid because of its highly complex systemic nature and the large number of stakeholders involved in its operation (O'Sullivan and Brévignon-Dodin, 2012). Recognising such importance and urgency of standards-related issues in the field, the Energy Independence Act of the US assigned NIST the 'primary responsibility to coordinate development of a framework… to achieve interoperability of smart grid devices and systems' (NIST, 2010, p. 7). NIST has subsequently developed the *NIST Framework and Roadmap for Smart Grid Interoperability Standards* to help guide and align the development of standards in the smart grid area (NIST, 2010).

As part of developing the framework and roadmap, NIST has identified 74 standards and guidelines (to early 2015) developed by various organisations, that support interoperability of smart grid devices and systems (NIST, 2014). As the NIST list appears to be the most advanced and updated in this field, a set of standards were selected from it for this case study to illustrate the effectiveness of the framework for capturing standardisation needs that have been addressed by standards with a range of roles, and that have been developed by a variety of SDOs. They were also selected to demonstrate the flexibility and effectiveness of the framework. The set of 12 standards selected can be seen in Table 3. The 'domain' column is included in the table as they are important categories distinguishing various actors and applications involved in smart grid technologies. Identifying the main domains of

Table 3
The standards used in the smart grid case study, selected for their variety and varying levels of interdependence.

Standard	Date	Title	Role	Domain	SDO
ANSI C12.1	2008	Code for electricity metering	Measurement/quality for revenue metering	Customer, service provider	ANSI
ANSI C12.21	2006	Protocol specification for telephone modem communication	Interoperability/interface b/w device and client	Customer, service provider	ANSI
IEC 60870-6-503	2002, rev in 2014	Telecontrol equipment and systems – TASE.2 services and protocol	Interoperability/interface b/w control centres	Transmission, distribution	IEC
IEC 61850-2	2003	Communication networks and systems in substations – glossary	Terminology for SAS	Transmission, distribution	IEC
IEC 61850-3	2002, rev in 2013	Communication networks and systems for power utility automation – general requirements	Quality for communication between IEDs	Transmission, distribution	IEC
IEC 61850-6	2004, rev in 2009	Communication networks and systems for power utility automation – configuration description language for communication in electrical substations related to IEDs	Information / variety reduction for communication between IED tools	Transmission, distribution	IEC
IEC 61850-7-2	2003, rev in 2010	Communication networks and systems for power utility automation – basic information and communication structure – Abstract Communication Service Interface (ACSI)	Interoperability/interface for utility automation	Transmission, distribution	IEC
IEC 61850-10	2005, rev in 2012	Communication networks and systems for power utility automation – conformance testing	Measurement/testing for power utility automation	Transmission, distribution	IEC
IEEE 1815	2012	Standard for electric power systems communications – Distributed Network Protocol (DNP3)	Interoperability/interface	Generation, transmission, distribution, operations, service provider	IEEE
IEEE 1547	2003, rev in 2014	Standard for interconnecting distributed resources with electric power systems	Interoperability for interconnecting distributed resources	Transmission, distribution, customer	IEEE
NAESB REQ18/ REQ19	2010	Energy usage information	Interoperability/interface for energy usage info.	Customer, service provider	NAESB
NEMA SG-AMI 1-2009	2009	Requirements for smart metre upgradeability	Quality requirement for AMI	Customer, distribution	NEMA

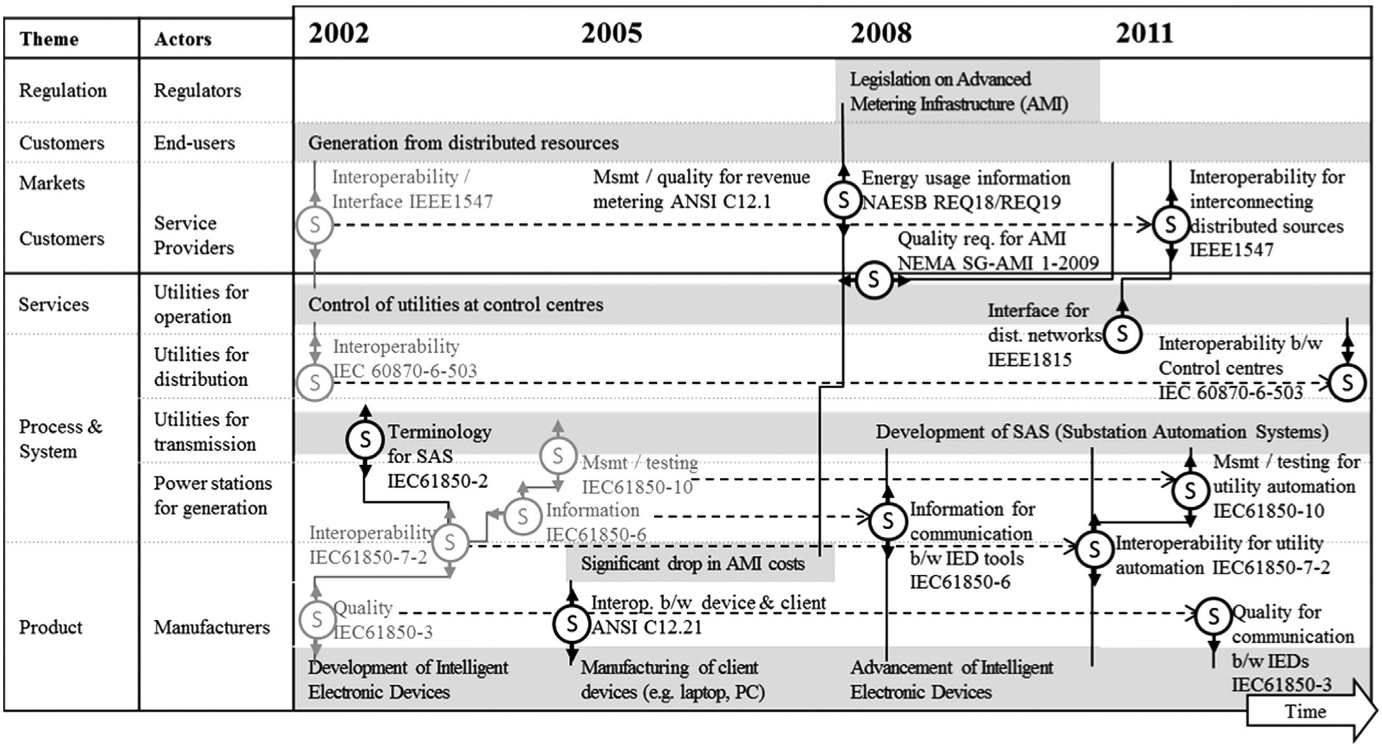

Fig. 4. Illustrative example of the framework for smart grid.

application (including generation, transmission, distribution, operation, service providers, and customers) helps understand which innovation activities and actors the particular standard transfers information and knowledge between and provide useful criteria for selecting aggregated innovation activities that contribute to smart grid innovation. Accordingly, the identified standards and relevant innovation activities, along with actors involved in these activities, are mapped onto the standards mapping framework developed in the previous section, an illustration of which can be seen in Fig. 4.

As smart grid refers to an integrated system of technologies rather than conducting research and development at basic science and technology levels (cf. synthetic biology and additive manufacturing), its innovation process mainly involves assembling and linking vast number of devices, products, processes and systems across various domains of smart grid technologies. To demonstrate the framework's ability to reflect these particular priorities, the identified standards were selected because they are communication protocols that establish linkages and interoperability between diverse products and systems, the absence of which may result in smart grid technologies becoming prematurely obsolete. Many standards are especially developed in the domains of transmission and distribution, as data exchange and communications need to be made between systems of different utility companies. Standards are also needed to define communication protocols for products and devices from different manufacturers, making them compatible and easily integrated with other smart grid systems.

In addition, various other stakeholders such as regulatory bodies and actors in markets might be involved, when electricity is exchanged in markets or relevant legislations are enacted. Therefore, in order to facilitate innovation of such complex, integrated systems involving various stakeholders, describing how particular products and systems need to be connected within a larger system is essential, as suggested by various scholars and practitioners (Blind and Gauch, 2009; BERR, 2008). Interoperability/interface Interoperability/interface standards play important roles in this, by supporting communication and establishing linkages across various domains. There are also various other standards with different functions, including information/terminology standards, and measurement/testing standards. For example, IEC 61850-2 contains the glossary of specific terminology and definitions used in the context of substations and IEC 61850-6 specifies a file format for describing device configurations. These standards appear at a relatively early stage of the overall technology lifecycle, suggesting that common terminology and information needs to be established early to facilitate efficient communication among various stakeholders, as noted by Blind and Gauch (2009). There exist other standards that also define recommended measurement techniques for testing of conformance and measuring performance levels, codifying and transmitting knowledge in the form of best practice between various domains involved in the system (Tassey, 2000). Therefore, the case study shows that the smart grid standards not only ensure successful integration of products and systems in different domains within a larger system, but also allow information generated and knowledge developed in one domain to be diffused into other domains, supporting further innovation.

In addition, the framework is flexible enough to capture various other strategic considerations and dimensions that need to be considered for standardisation strategy development. Standards developed by various organisations with varying approaches, from working groups or technical committees of official SDOs to professional consortiums developing public standards, can be mapped over time. It also captures how standards revisions may be necessary due to revisions of related standards triggered by technological changes and advancements, as can be seen from the successive revision of IEC 61850 series regarding communication networks and systems for power utility automation. This further emphasises the sequencing issues identified in the in the previous case studies.

5. Discussion

5.1. Linking standardisation to the process of innovation

The case studies suggest that standardisation can play a significant role in supporting the specific diffusion needs of innovation activities. This supports the view that standards are enablers of information and knowledge diffusion and help to bridge the gap between research and markets (European Commission, 2011; Blind and Gauch, 2009). The case studies indicate that the proposed technology roadmapping-based framework helps to better reveal how standards-related activities can support the innovation pathway of emerging technologies. The framework does this by more carefully identifying (aggregated) innovation activities and associated opportunities for standardisation based on their diffusion needs.

The case studies also suggest that standards not only support information and knowledge diffusion, but also help mediate between innovation activities and between actors. The standards in the case studies not only help structure and communicate necessary information, but also facilitate its generation (for example, testing in additive manufacturing) and structure how it is communicated both ‘forward' to downstream and ‘back' to upstream innovation activities (for example, how to describe system elements in synthetic biology). This supports standards as a mechanism for aligning and coordinating innovation activities. The case studies also suggest this mediating function incorporates a ‘multilateral nature', where standards can be developed to consider both technology-push and demand-pull factors, and where such considerations mutually affect the actors involved. For example, the ISO additive manufacturing standard for Part specification (BS/ISO 17296-4, 2014) identifies not only how a part should be specified for a part user, but also how the user can specify the requirements to manufacturers. These findings support Yoo et al.'s (2005) argument that standards help mediate the interests of different actors.

Beyond diffusion and mediation, the case studies also suggest that standards enhance and catalyse innovation. Tassey (2000) asserts that a number of activities already taking place are enhanced by standards, providing examples such as allowing ‘factories to achieve economies of scale and enabled markets to execute transactions in an equitable and efficient manner' (p. 588). This enhancement can occur in a number of areas, including making these activities cheaper, easier, and faster. The aggregated innovation activities in the case studies also indicate the catalytic nature of standards. For example, the terminology and semantics standards developed for synthetic biology (the development of these rules is itself an innovation activity) enable communication between researchers, developers, and designers, catalysing renewed activity based on the flow of new information and knowledge. These functions – diffusion, mediation, enhancement, and catalysis – are important functions standards can play in supporting technology emergence.

5.2. Drawing attention to some central considerations for standardisation strategies

While the case studies indicate that standards can be designed to help diffuse information and knowledge, mediate between innovation actors, and enhance and catalyse innovation activities, they also show how the framework has the potential to help coordinate and align standardisation activities. In the synthetic biology and smart grid case studies, for example, a revision of one standard prompted the revision of other dependent standards. The framework can thus help manage a portfolio or ‘system' of standards, by identifying and capturing the links between relevant innovation activities and between related standards.

The case studies also illustrate how the framework can be used to indicate which stakeholders might need to be involved in standards development. Through the characterisation of innovation activities, the framework can be used to link anticipated standardisation activities with the relevant innovation actors, further informing sequencing- and revision-related needs by suggesting the relevant stakeholders to involve. In addition, the framework can support the exploration of the possible roles of government and government agencies in standardisation, specifically where they can undertake leadership, coordinating, or convening functions to further promote standardisation activities.

The case studies reinforce Blind and Gauch's (2009) argument that particular types of standards are associated with particular stages of a technology lifecycle. The synthetic biology case study, for example, suggests that semantic standards are developed in the early stages of a technology lifecycle, linking *pure basic research* to *oriented basic research* (Blind and Gauch, 2009). Standards in other case studies link different stages of technology lifecycle identified by Blind and Gauch (2009), including additive manufacturing's measurement and testing standards (bridging to *applied research*); smart grid's interface standards (bridging to *experimental development*); and various compatibility, quality, and variety reduction standards (bridging to *technology diffusion*). However, despite the varying maturity of the fields addressed in the case studies, the timing of particular types of standards are not reflected as clearly or as linearly as Blind and Gauch (2009) suggest. This is possibly due to the nonlinearity of technology development (acknowledged by Blind and Gauch (2009)), the different timeframes between identification of standards needs and their publication, the various technologies within each field being at different stages of development or the commonly observed characteristic of emerging technologies to continually draw from the science-base to upgrade their technical functionality and other features (e.g., design aesthetics). Nevertheless, one obvious trend in all case studies is the early development of terminology standards, confirming Blind and Gauch's (2009) argument and Ho and O'Sullivan's (2013) findings that these standards are some of the earliest to be developed.

The case studies also demonstrate that the established flexibility and scalability of technology roadmapping has been retained. They indicate that the framework can accommodate a range of different types of standards, in different domains, with different actors, and applied to different end markets and that the horizontal categories proved to be easily selected and removed from the framework for reasons of relevance and the clear visualisation of standardisation opportunities.

The literature relating to standards, supported by the case studies, suggest that important considerations for developing standardisation strategies include: the different standardisation needs of different stages of technology development, the different types of standards that can be developed, the evolving composition of stakeholders, and the timing and sequencing of different standards. The case studies offer a proof of principle that the framework is capable of capturing these strategic considerations and dimensions. Furthermore, the case studies suggest that these considerations and dimensions are interdependent, hence there is potentially considerable benefit in being able to explore and consider them jointly.

Furthermore, scanning activities could be guided by the framework to identify potentially competing standards and those in closely related technology fields. For instance, some standards developed for systems biology can also be used to support synthetic biology-based products and processes. Scanning for, and mapping, such standards help to not only provide ‘anticipatory intelligence to system actors,' but also ‘inform policy' and strategy development, which are key characteristic of foresight exercises

(Miles et al., 2008, p. 20), and could help streamline standardisation processes.

5.3. Implications of the framework

The framework neither suggests that all standards requirements can be anticipated, nor recommends making all identified standards *de jure*. Instead it is suggested that the framework can be used to identify standardisation opportunities. This view indicates that the framework could also identify standards that might emerge naturally from interactions ('unsponsored' *de facto* standards), as well as those that could be formally developed either by SDOs or governments (*de jure* standards) or by industry consortia or firms ('sponsored' *de facto* standards).

The historical approach embraced in the case studies demonstrates the principles of the framework and indicates its validity as a means of capturing the relevant innovation considerations and dimensions to reveal important standardisation opportunities and needs. By capturing these considerations and dimensions, the case studies provide an early 'proof of concept' and suggest applying the framework in an anticipatory setting. An example of how standards anticipation may be depicted is given in the additive manufacturing case study. The example indicates that the framework has retained the intrinsic future orientated focus of technology roadmapping, a core characteristic of technology foresight. A practical application, and its assessment over time, is recommended to evaluate just how useful the framework is for anticipating future standardisation opportunities.

6. Conclusions

The presented framework is designed to inform where standardisation may be important and where efforts could be invested to overcome particular challenges related to the development of emerging technologies. The proposed framework incorporates a number of critical strategic considerations and dimensions important for standards development, including technological innovation activities, standards types, SDOs and participants, and the timing of standards. The framework was anchored in technology roadmapping, a practical technology innovation framework that takes account of complex technical systems and spans key areas of risk, opportunity, and challenges. This foundation helps the framework to draw out the *innovation activities* and technology development's *time* dependent nature. The proposed framework builds on these features, adding the consideration of multiple *types of standardisation* and explicitly identifying the relevant, and changing, composition of *stakeholders*. The proposed framework combines these features (strategic considerations and dimensions), using a more detailed characterisation of innovation activities to reveal where standardisation might be used to diffuse information and knowledge, mediate between innovation actors, and potentially enhance and catalyse innovation activities, ultimately supporting an emerging technology.

The framework could be used to leverage current or past technology roadmapping exercises to identify standardisation needs. At the very least, the proposed framework's key dimensions could be used to point to potentially important standardisation opportunities and challenges in existing standardisation or technology foresight exercises.

Three 'historical' case studies of recent emerging technologies were offered as a 'proof of principle' and to demonstrate the utility of the framework. The case studies suggest that the proposed framework can capture and bring clarity on the aforementioned strategic considerations and dimensions and to other strategic considerations that might otherwise be overlooked, including alignment, coordination, and sequencing. All of these considerations and dimensions proved critical to understanding the role of standardisation in the emergence of the case study technologies. The importance and relevance of the above considerations enhance previous contributions to the literature on standards.

Furthermore, the historical case studies indicate that the framework was customisable enough to reflect a variety of innovation activities, capture a variety of different roles standards fulfil, and accommodate different types of standards, while retaining the flexibility and adaptability of technology roadmapping.

The case studies also suggest that standards support technology development in a rich and complex way, uphold the findings described in a number of publications (including Tassey, 2000). However, the case studies also point to the importance of the appropriate design, timing, and coordination of standards, bolstering Allen and Sriram's (2000) claims that standards can both help and hinder technological development. This urges caution when developing standards specifically to support technology development.

The strategic considerations and dimensions underpinning the framework (time, innovation activities, stakeholders, and standardisation types) help reveal information that can help to avoid hindering technology development and support the development of an appropriately designed and coordinated portfolio of standards. The clarity provided by the framework, and the visual form it can take (see the case studies), can help navigate the complexity involved in the development of such standardisation strategies, which, as suggested by their potential to both facilitate and hinder technology development, should be an integral part of technology development strategies.

More specifically, the framework, through such standardisation strategies, can also be used to inform technology investment decisions – either in standards or technology development directly – and grant conditions, for example including standards development exercise participation conditions, as called for by the European Commission (2008) and suggested by CEN and CENELEC (2012; 2014).

Future research should test the framework in a greater variety of technical domains and review its efficacy at anticipating relevant and applicable standardisation needs. Further research could also link the framework and its anticipated standards more closely to the functions of innovation systems approaches (Johnson, 2001; Bergek et al., 2010), to establish just how these informed standards are facilitating the functioning of the innovation system.

Finally, our case studies show that standardisation is not just bureaucracy, not just about diffusing 'rules', not just something that happens after all the key research and innovation breakthroughs have taken place. They suggests that standardisation can happen from the earliest phases of technology emergence, mediates many critical innovation activities, and embodies many fundamental characteristics of innovation itself including its evolutionary, feedback-driven, nonlinear nature. Consequently, a detailed, sophisticated, and systemic consideration of standardisation should be an integral part of a comprehensive emerging technology strategy. The framework proposed here can be deployed to make an early contribution to the development of such strategies.

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References

Allen, R.H., Sriram, R.D., 2000. The role of standards in innovation. Technol. Forecast. Soc. Chang. 64 (2–3), 171–181.
Amer, M., Daim, T.U., 2010. Application of technology roadmaps for renewable energy sector. Technol. Forecast. Soc. Chang. 77 (8), 1355–1370.
ANSI, 2014. ANSI Essential Requirements: Due process requirements for American National Standards. American National Standards Institute (ANSI), New York, NY.
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. Edward Elgar, Cheltenham, UK, pp. 115–144.
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 (3), 407–429.
BERR, 2008. Regulation and innovation: evidence and policy implications (BEER Economics Paper No. 4). Department for Business, Enterprise and Regulatory Reform (BERR), London, UK.
Blackwell, A.F., Phaal, R., Eppler, M., Crilly, N., 2008. Strategy Roadmaps: New Forms, New Practices, 5th International Conference on Diagrammatic Representation and Inference. Springer-Verlag, Berlin & Heidelberg, Germany, pp. 127–140.
Blind, K., Gauch, S., 2009. Research and standardisation in nanotechnology: evidence from Germany. J. Technol. Transf. 34 (3), 320–342.
Blind, K., Gauch, S., Hawkins, R., 2010. How stakeholders view the impacts of international ICT standards. Telecommun. Policy 34 (3), 162–174.
BMBF, 2010. Ideas. Innovation. Prosperity. High-Tech Strategy 2020 for Germany. Federal Ministry of Education and Research, Bonn, Germany.
Bourell, D.L., Leu, M.C., Rosen, D.W., 2009. Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing. Laboratory for Freeform Fabrication Advanced Manufacturing Center. The University of Texas at Austin, Austin, TX.
Bourell, D.L., Rosen, D.W., Leu, M.C., 2014. The roadmap for additive manufacturing and its impact. 3D Print. Addit. Manuf. 1 (1), 6–9.
Brévignon-Dodin, L., O'Sullivan, E., 2013. Standards development in support of the Europe 2020 "smart growth" objective – Evidence from Germany and the USA. In: 17th EURAS Annual Standardisation Conference: Boosting European Competitiveness, Brussels, Belgium.
Brady, R.A., 1933. The Rationalization Movement in German Industry. University of California Press, Berkeley.
Bryant, J.G., Benfer, J.E., Petrizzo, A.B., 2013. Measurement Barriers in the Implementation of Metals Additive Manufacturing for Military Aircraft Repair and Maintenance, Energetics Incorporated (Ed.), Measurement Science Roadmap for Metal-Based Additive Manufacturing. Prepared for the National Institute of Standards and Technology (NIST). NIST, Columbia, MD, pp. 63–64 (NAVAIR J., FRCSE).
BSI, 2006. Introducing Standards. British Standards Institute (BSI), London, UK.
CEN, CENELEC, 2012. Integrating Standards in Your FP7: Linking R&D and Standardization. European Committee for Standardization (CEN) and European Committee for Electrotechnical Standardization (CENELEC), Brussels, Belgium.
CEN, CENELEC, 2014. Integrating Standards in Your Horizon 2020 Project: Linking Innovation and Standardization. European Committee for Standardization (CEN) and European Committee for Electrotechnical Standardization (CENELEC), Brussels, Belgium.
Choi, D.G., Lee, H., Sung, T., 2011. Research profiling for "standardization and innovation". Scientometrics 88 (1), 259–278.
Cisco Systems, 2003. Vision 2010: The Retail Roadmap for Chief Executives. Cisco Syst., Inc., San Jose, CA.
Dosi, G., 1982. Technological paradigms and technological trajectories. Res. Policy 11 (3), 147–162.
Edquist, C., 1999. Innovation Policy – A Systemic Approach. Department of Technology and Social Change Working Paper, Linköping University, Linköping.
Ehrnberg, E., Jacobsson, S., 1997. Technological Discontinuities and Incumbents' Performance: An Analytical Framework. In: Edquist, C. (Ed.), Systems of Innovation: Technologies, Institutions and Organizations. Pinter, London, UK, pp. 318–341.
Endy, D., 2005. Foundations for engineering biology. Nature 438, 449–453.
European Commission, 2013. 2013 Rolling Plan for ICT Standardisation. European Commission, Brussels, Belgium.
European Commission, 2008. Communication from the commission. Towards an Increased Contribution from Standardisation to Innovation in Europe. European Commission, Brussels, Belgium.
European Commission, 2011. Communication from the commission. A Strategic Vision For European Standards: Moving Forward to Enhance and Accelerate the Sustainable Growth of the European Economy by 2020. European Commission, Brussels, Belgium.
EXPRESS, 2010. Standardization for a Competitive and Innovative Europe: A Vision for 2020.
Featherston, C.R., Ho, J.-Y., Brévignon-Dodin, L., O'Sullivan, E., 2014. Technology Roadmapping Approach in Support of Standardisation Needs for Emerging Technologies: Guiding and Structuring the Exploration of Standards Needs. Institute for Manufacturing, University of Cambridge, Cambridge, UK.
Foray, D., 1998. Standards and innovation in technological dynamics. StandardView 6 (2), 81–84.
Gandal, N., 1995. Competing Compatibility Standards and Network Externalities in the PC Software Market. Rev. Econ. Stat. 77 (4), 600–608.
Garcia, M., Bray, O., 1997. Fundamentals of Technology Roadmapping. Sandia National Laboratories, Albuquerque, NM.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31 (8–9), 1257–1274.
Groenveld, P., 1997. Roadmapping integrates business and technology. Res. Technol. Manag. 40 (5), 48–55.
Groenveld, P., 2007. Roadmapping integrates business and technology. Res. Technol. Manag. 50 (6), 49–58.
Hanseth, O., Monteiro, E., Hatling, M., 1996. Developing information infrastructure: the tension between standardization and flexibility. Sci. Technol. Hum. Values 21 (4), 407–426.
Hatto, P., 2010. Standards and Standardization Handbook. European Commission, Brussels, Belgium.
Heseltine, Lord, 2012. No Stone Unturned in Pursuit of Growth. Department of Business, Innovation and Skills (BIS), London, UK.
HLG KET, 2011. High-Level Expert Group on Key Enabling Technologies: Final Report. European Commission, DG Enterprise and Industry, Brussels, Belgium.
Ho, J.-Y., O'Sullivan, E., 2013. Evolving Roles of Standards in Technological Innovation – Evidence from Photovoltaic Technology. In: Proceedings of the 35th DRUID Celebration Conference, Barcelona Spain.
Ho, J.-Y., O'Sullivan, E., 2014. Defining and Categorising 'Standards' in Innovation. Working Paper. Centre for Science Technology and Innovation Policy, University of Cambridge.
IBM, 2002. Integrated Multi-channel Retailing (IMCR): A Roadmap to the Future. IBM Corporation, Somers, NY.
ISO, 2004. Standardization and related activities — General vocabulary. ISO/IEC Guide, 2.
Jereza, K., Brindle, R., Williams, G., Chappell, J., 2005. Magnesium Casting Industry Technology Roadmap. American Foundry Society, Columbia, MD, Energetics Incorporated.
Johnson, A., 2001. Functions in innovation system approaches. In: Documento Presentado a la Conferencia Nelson-Winter, Aalborg, Denmark, pp. 1–19.
Keasling, J., 2005. The promise of synthetic biology. Bridge 35 (4), 18–21.
Keenan, M., 2003. Identifying emerging generic technologies at the national level: the UK experience. J. Forecast. 22 (2–3), 129–160.
Kostoff, R.N., Schaller, R.R., 2001. Science and technology roadmaps. IEEE Trans. Eng. Manag. 48 (2), 132–143.
Lee, S., Park, Y., 2005. Customization of technology roadmaps according to roadmapping purposes: overall process and detailed modules. Technol. Forecast. Soc. Chang. 72 (5), 567–583.
Liou, F., 2013. Measurement Science Barriers and R&D Opportunities for the NIST Metal-Based AM Workshop. In: Energetics Incorporated (Ed.), Measurement Science Roadmap for Metal-Based Additive Manufacturing. National Institute of Standards and Technology (NIST), Columbia, MD, pp. 61–62.
Lundvall, B.-Å., 1992. National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning. Pinter, London, UK.
Metcalfe, J.S., Miles, I., 1994. Standards, selection and variety: an evolutionary approach. Inf. Econ. Policy 6 (3), 243–268.
Miles, I., Harper, J.C., Georghiou, L., Keenan, M., Popper, R., 2008. The Many Faces of Foresight. In: Georghiou, L., Harper, J.C., Keenan, M., Miles, I., Popper, R. (Eds.), The Handbook of Technology Foresight: Concepts and Practice. Edward Elgar, Cheltenham, UK, pp. 3–23.
NAKFI, 2010. National Academies Keck Future Initiative on Synthetic Biology: Building a Nation's Inspiration: Interdisciplinary Research Team Summaries. The National Academies Press, Washington, D.C.
NASA, 2010. Global Exploration Roadmap. NASA, Washington D.C.
NIST, 2010. NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0. NIST, Gaithersburg, MD.
NIST, 2011. Effectiveness of Federal Agency Participation in Standardisation Activities in Select Technology Sectors: Summary of the responses to the National Science and Technology Council's Sub-Committee on Standards Request-for-Information. NIST, Gaithersburg, MD.
NIST, 2012. NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0. NIST, Gaithersburg, MD.
NIST, 2014. NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0. NIST, Gaithersburg, MD.
NSTC, 2011a. National Nanotechnology Initiative: Strategic Plan. Executive Office of the President of the United States, Washington, D.C.
NSTC, 2011b. Federal Engagement in Standards Activities to Address National Priorities: Background and Proposed Policy Recommendations. Executive Office of the President of the United States, Washington, D.C.
NSTC, 2014. National Nanotechnology Initiative: Strategic Plan. Executive Office of the President of the United States, Washington, D.C.
O'Sullivan, E., Brévignon-Dodin, L., 2012. Role of Standardisation in support of Emerging Technologies. Institute for Manufacturing, University of Cambridge, Cambridge, UK.
Phaal, R., Muller, G., 2009. An architectural framework for roadmapping: towards visual strategy. Technol. Forecast. Soc. Chang. 76 (1), 39–49.

Phaal, R., Farrukh, C.J.P., Probert, D.R., 2004. Customizing roadmapping. Res. Technol. Manag. 47 (2), 26–37.
Phaal, R., Farrukh, C.J.P., Probert, D.R., 2009. Visualising strategy: a classification of graphical roadmap forms. Int. J. Technol. Manag. 47 (4), 286–304.
Phaal, R., Farrukh, C.J.P., Probert, D.R., 2010. Roadmapping for Strategy and Innovation: Aligning Technology and Markets in a Dynamic World. Institute for Manufacturing, University of Cambridge, Cambridge, UK.
Phaal, R., O'Sullivan, E., Routley, M.J., Ford, S.J., Probert, D.R., 2011. A framework for mapping industrial emergence. Technol. Forecast. Soc. Chang. 78 (2), 217–230.
Popper, R., 2008. Foresight Methodology. In: Georghiou, L., Harper, J.C., Keenan, M., Miles, I., Popper, R. (Eds.), The Handbook of Technology Foresight. Edward Elgar, Cheltenham, UK, pp. 44–88.
Sahal, D., 1985. Technological guideposts and innovation avenues. Res. Policy 14 (2), 61–82.
SASAM, 2014. Additive Manufacturing: SASAM Standardisation Roadmap. The European Technology Platform Manufuture: s.l., Europe.
Scapolo, F., Churchill, P., Viaud, P., Antal, M., Cordova, H., Smedt, P., 2014. Final Report of the Foresight Study on "How will Standards Facilitate New Production Systems in the Context of EU Innovation and Competitiveness in 2025?". European Commission – Joint Research Centre, Brussels, Belgium.
Sherif, M., 2001. A framework for standardization in telecommunications and information technology. IEEE Commun. Mag., 94–100, April.
Silverman, P.J., 2002. The Intel Lithography Roadmap. Intel. Technol. J. 6 (2), 55–61.
Smith, K., 1997. Economic Infrastructures and Innovation Systems. In: Edquist, C. (Ed.), Systems of Innovation: Technologies, Institutions and Organizations. Pinter, London, UK, pp. 86–106.
Swann, G.M.P., 2010. The economics of standardization: an update. Report for the UK Department of Business, Innovation and Skills (BIS).
Swann, G.M.P., 2000. The economics of standardization. Final Report for Standards and Technical Regulations Directorate, Department of Trade and Industry (DTI).
Tassey, G., 2000. Standardization in technology-based markets. Res. Policy 29 (4–5), 587–602.
Tassey, G., 2005. Underinvestment in public good technologies. J. Technol. Transf. 30 (1–2), 89–113.
Tassey, G., 2007. The Technology Imperative. Edward Elgar, Cheltenham, UK.
TESSY, 2008. Final Report: TESSY Achievements and Future Perspectives in Synthetic Biology. Fraunhofer Institute Systems and Innovation Research, Karlsruhe, Germany.
Torrance, A.W., Kahl, L.J., 2012. Bringing Standards to Life: Synthetic Biology Standards and Intellectual Property. St. Clara High. Technol. Law J. 30, 2.
TSB, 2012. A Synthetic Biology Roadmap for the UK. Technology Strategy Board (TSB), London, UK.
US International Trade Commission, 1990. The Effects of Greater Economic Integration Within the European Community on the United States: First Follow-up Report. US International Trade Commission, Washington, D.C., USA.
Utterback, J.M., 1994. Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change. Harvard Business School Press, Boston, MA.
Van de Ven, A.H., 1993a. A community perspective on the emergence of innovations. J. Eng. Technol. Manag. 10 (1–2), 23–51.
Van de Ven, A.H., 1993b. The development of an infrastructure for entrepreneurship. J. Bus. Ventur. 8 (3), 211–230.
Wang, J., Kim, S., 2007. Time to get in: the contrasting stories about government interventions in information technology standards (the case of CDMA and IMT-2000 in Korea). Gov. Inf. Q. 24 (1), 115–134.
Willetts, R.H.D.M., 2013. Eight Great Technologies. Policy Exchange, London, UK.
Yoo, Y., Lyytinen, K., Yang, H., 2005. The role of standards in innovation and diffusion of broadband mobile services: the case of South Korea. J. Strateg. Inf. Syst. 14 (3), 323–353.