A SYSTEMS PERSPECTIVE ON STANDARDISATION IN TECHNOLOGICAL INNOVATION:

A Conceptual Framework and a Process Model
Supporting Strategic Policy Foresight

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ABSTRACT

A Systems Perspective on Standardisation in Technological Innovation:

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This thesis addresses conceptual and practical challenges in anticipating potential standardisation needs and developing relevant strategies throughout various stages of technological innovation. With increasing awareness of critical roles played by standardisation in supporting a variety of innovation activities, strategic foresight for timely and appropriate standardisation is becoming a crucial innovation policy interest in many countries. However, there are currently limited and fragmented studies on this issue, because of the complexity and variety involved in dynamic interplays between standardisation and other aspects of innovation. There are also increased challenges to develop coherent and long-term strategies for standardisation, due to modern technologies that are becoming more complex, interdisciplinary, and fast-evolving at the same time. Standards organisations and policymakers thus face significant challenges in developing standardisation strategies (in terms of what, why, when, how, and who) to support technological innovation more effectively.

In this regard, the current research develops a systematic conceptual framework for more comprehensive understanding of standardisation – particularly highlighting its technological complexities – in the context of innovation, and a structured process model for using it to support strategic policy foresight. Building on the innovation systems perspective, preliminary framework and process model are first developed by adopting the holistic approach of strategic roadmapping as method, and incorporating *a priori* constructs drawn from existing literature relevant to standardisation. Then, multiple exploratory case studies covering various technology domains have been conducted to identify first order elements for their development. They are followed by an in-depth longitudinal case study on standardisation of photovoltaic technology, testing and refining the framework and process model by exploring complex dynamics between standardisation and innovation in greater detail. Interviews with experts across a broader range of domains and regions have then been carried out, to verify the framework and process model, including their utility and practicality.

This thesis makes contributions to both theory and practice. With a systems perspective on standardisation, it provides a more holistic and comprehensive understanding of how standardisation supports innovation, highlighting its mediating roles between critical innovation activities and functions. It also presents a unified framework integrating various dimensions of standardisation with particular emphasis on technological elements, addressing challenges due to complex technological systems. Such new insights are expected to help standards organisations and policymakers with strategic foresight for standardisation in support of innovation, using the proposed framework and process model as practical tools for anticipating future standardisation needs and developing relevant strategies. In addition, the current research contributes to the roadmapping literature and practice, by presenting more structured and advanced frameworks and processes, and providing insights for using the roadmap-based approach as methods for data collection and analyses.

PREFACE

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specified in the text.

No part of the dissertation has been previously submitted to any university for any degree, diploma, or other qualification.

This dissertation contains 31 figures and approximately 65,000 words. It is therefore within the limits allowed by the Degree Committee of the Engineering Department.

In addition, four journal papers have been developed from this PhD study:

J. Y. Ho and E. O'Sullivan (2016) The multi-dimensional nature of standardisation in support of innovation: A systematic analysis of the history of photovoltaic technology. (R&R)

J. Y. Ho and E. O'Sullivan (2016) Strategic standardisation of smart systems: A roadmapping process in support of innovation. *Technological Forecasting and Social Change* (In press)

C. Featherston, J. Y. Ho, L. Brévignon-Dodin, and E. O'Sullivan (2016) Mediating and catalysing innovation: A framework for anticipating the standardisation needs of emerging technologies. *Technovation*, 48-49, pp. 25-40.

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ABBREVIATIONS

AFNOR	Association Française de Normalisation (French Association for Standardisation)
AMI	Advanced Metering Infrastructure
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BIS	Department of Business, Innovation, and Skills of the UK
BOS	Balance of Systems
BSI	British Standards Institution
CEN	Comité Européen de Normalisation (European Committee for Standardisation)
CENELEC	Comité Européen de Normalisation Électrotechnique (European Committee for Electrotechnical Standardisation)
CPV	Concentrating Photovoltaic
DIN	Deutsches Institut für Normung (German Institute for Standardisation)
DKE	Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE (German Commission for Electrical, Electronic & Information Technologies of DIN and VDE)
EN	European Standard
ETRI	Electronics and Telecommunications Research Institute of Korea
ETSI	European Telecommunications Standards Institute
FSO	Formal Standards Organisation
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IS	International Standard
ISO	International Organisation for Standardisation
IIEEJ	Institute of Image Electronics Engineers of Japan
ITU	International Telecommunication Union
JPL	Jet Propulsion Laboratory
KARUS	Korea Association of RFID/USN Convergence
KATS	Korean Agency for Technology and Standards

KSA	Korean Standards Association
KRISS	Korea Research Institute of Standards and Science
NABCEP	North American Board of Certified Energy Practitioners
NAESB	North American Energy Standards Board
NEC	National Electrical Code of the US
NEMA	National Electrical Manufacturers Association of the US
NGO	Non-Governmental Organisation
NIA	National Information Society Agency
NIST	National Institute of Standards and Technology of the US
NPE	National Platform for Electromobility of Germany
NRECA	National Rural Electric Cooperative Association of the US
NREL	National Renewable Energy Laboratory of the US
OASIS	Organisation for the Advancement of Structured Information Standards
OPV	Organic Photovoltaic
PAS	Publicly Available Specification
PV	Photovoltaic
R&D	Research and Management
REQ	Requirement
SASAM	Support Action for Standardisation in Additive Manufacturing
SDO	Standards Developing Organisation
SEIA	Solar Energy Industry Association of the US
SEMI	Semiconductor Equipment and Materials International
Solar ABC	Solar America Board for Codes and Standards
SSC	Standards Coordinating Committee
SSO	Sectoral or Specialised Standards Organisations
TC	Technical Committee
TR	Technical Report
TS	Technical Specification
TTA	Telecommunications Technology Association of Korea
UL	Underwriters Laboratory
VDE	Verband der Elektrotechnik, Elektronik und Informationstechnik (Association for Electrical, Electronic and Information Technologies) of Germany
W3C	World Wide Web Consortium
WA	Workshop Agreement
WG	Working Group

1. INTRODUCTION

There are increasing needs for systematic and future-oriented analyses for timely and appropriate standardisation in support of innovation, as modern technologies become more complex, interdisciplinary, and fast-evolving. Despite its importance, there are significant challenges due to limited studies on, and dual nature of, standardisation – both supporting and inhibiting – in technological innovation. With these research background and motivation, research questions for the current thesis are defined, to develop a systematic framework for exploring complex and dynamic interplays between standardisation and innovation, and strategic processes that standards organisations and policymakers can use for standardisation foresight. A brief description of the research approach used to answer the research questions is also presented, followed by the structure of this thesis.

1.1 Research Background & Motivation

With increased industrialisation and globalisation, standards have long been understood by economists and policymakers as important public infrastructure supporting industrial competitiveness and economic development, by maximising efficiency in trade and the markets (e.g., David 1987; OTA 1992; Hawkins et al. 1995). During the last decades of the 20th century, the growth of Information and Communications Technology (ICT), where interoperability standards are critical to allow the interconnection of various technical components and systems, has also raised awareness of the importance of standards and their strategic management for technological innovation (Branscomb & Kahin 1995; Blumenthal & Clark 1995).

More recently, with the prevalence of systematic perspectives on technological innovation, standards are increasingly recognised by various academics and practitioners as important institutions that underpin innovation by disseminating new ideas and transferring useful knowledge (e.g., Van de Ven 1993; CIE 2006; European Commission 2011). As a result, a number of studies from different theoretical traditions – including technological systems (e.g., Allen & Sriram 2000; Tassey 2000), economics (e.g., Blind & Gauch 2009; Swann 2010), management (e.g., Tushman & Rosenkopf 1992), sociology (e.g., Hanseth et al. 1996), and standardisation practices (e.g., Hatto 2013) – have been recently carried out, exploring diverse roles of standards in supporting a variety of innovation activities. They include: defining and establishing common foundations upon which innovative technology may be developed; codifying and diffusing state-of-the-art technology and best practice; and allowing interoperability between and across products and systems (Allen & Sriram 2000; Tassey 2000; Blind & Gauch 2009; Swann 2010; NSTC 2011). Recognising such critical roles of standards in supporting innovation, many countries increasingly adopt policy initiatives for timely and effective standardisation (e.g., CSTP 2010; White House 2011), to secure national competitiveness and promote their innovation systems (Biddle et al. 2012; Choi 2013).

This understanding of the supporting role of standardisation in innovation contrasts with a still common perception that standards intrinsically limit technological options, potentially inhibiting creativity and change associated with innovation (e.g., Brady 1933). A number of articles in both academic and practice literature discuss the constraining impact of inappropriate and untimely standards on innovation, increasing irreversibility and decreasing the interpretative flexibility of technologies (Hanseth et al. 1996; Foray 1998; Swann 2010). For example, health and safety standards for consumer protection may lead to firms focusing on fewer technological options which, in turn, result in reduced innovation activities (BERR 2008). There may also be problems of lock-in to inferior standards or increased risks of monopolies, both of which are potentially detrimental to innovation (Swann 2000; CIE 2006).

Due to this dual impact of standardisation, both supporting and inhibiting innovation, strategic management for development and implementation of appropriate standards in a timely manner is critical in innovation policy. Many Standards Developing Organisations (SDOs) and policymakers across the world thus recognise needs for systematic and future-oriented analyses to anticipate standardisation needs and develop relevant strategies, in order to better support emerging technologies and their innovation systems (EXPRESS 2010; European Commission 2011; NSTC 2011; Scapolo et al. 2014). Despite such increasing awareness in practice, only a few studies (e.g., Goluchowicz & Blind 2011) have discussed this issue at a public policy level, as the existing literature on strategic standardisation have generally explored it from business and management perspectives (e.g., Betancourt & Walsh 1995; Shapiro & Varian 1999). In addition, various scholars adopting different disciplinary perspectives discuss only certain aspects or features of standardisation from their limited views, rather than taking a systems perspective (Narayanan & Chen 2012). There is, thus, limited knowledge and understanding on strategic planning and management of standardisation in broader innovation systems.

Such limited literature is probably due to the complex and uncertain nature of innovation systems, as well as complex dynamics involved in standardisation. There are varying levels of technical details associated with standards, various roles they play in technological innovation, and a variety of stakeholders involved with different interests; all of these not only interact with each other, but also evolve over time as innovation progresses, further complicating these dynamics (Allen & Sriram 2000; Tassey 2000; Sherif 2001; Swann 2010; Muller 2016). Hence, it is extremely challenging to understand complex interactions between these various dimensions of standardisation (i.e., broad categories of elements and factors characterising dynamics of standardisation in technological innovation) and other aspects of innovation, which are critical information for standardisation foresight.

The challenge with systematic and future-oriented analyses of standardisation in support of innovation is becoming even more significant with recent trends in complex technological systems, which are characterised by their highly interdisciplinary nature, growing role of ICT, and fast pace of technology and market developments. The increasing systems characteristic of modern industries requires a large infrastructure of standards that allow integration of various technologies and (sub-)systems with different characteristics, and capture greater value from complex supply chains (Blumenthal & Clark 1995; Tassey 2015; Muller 2016). The growing importance of ICT in a variety of industrial areas – such as smart grid and internet of things – also presents significant challenges in anticipating needs for compatibility and interoperability standards in a timely manner, especially during early stages of R&D with high uncertainties and risks (Ernst 2009; Biddle et al. 2012). In addition, standardisation in such complex areas calls for more coordinated and aligned activities among various stakeholders from the growing number of industry sectors involved, with different interests and perspectives (Ernst 2009; Biddle et al. 2012).

In order to overcome these challenges, further research is needed to develop a systematic framework that effectively captures various dimensions of standardisation in the context of technological innovation, for exploring their complex and dynamic interplays from broader perspectives. Practical processes are also needed, in order to use this information to support strategic management and foresight of standardisation, addressing the issue of engaging and coordinating various stakeholders involved in standardisation of complex technological systems.

1.2 Research Focus

The current thesis is concerned with strategic frameworks and processes for systematic and future-oriented analyses of standardisation in the context of technological innovation. Three clarifications need to be made at this point, in order to define a clear focus of the research.

First, the thesis focuses on aspects of innovation that are particularly relevant to technology development and associated complexities, such as the evolving technological functionalities, user needs, and levels of systems complexity. As defined by Dosi (1988, p.222), innovation concerns any activities related to "the search for, and the discovery, experimentation, development, imitation, and adoption of new products, new production processes, and new organisational set-ups." Among them, technology-related issues and their consequences on other aspects of innovation are considered to be particularly relevant to standardisation, given increased challenges due to the complex, interdisciplinary, and fast-paced nature of modern technologies. Thus focusing on technical complexities associated with standardisation in greater detail, this thesis pays less attention to those issues that are not directly related to technology development, such as business models and international trade.

Second, the thesis focuses on strategic foresight analyses of standardisation at a policy level, with long-term views of innovation systems; it is distinct from, and not to be confused with those at firm levels. Because of increased challenges in standardisation of complex, interdisciplinary technologies, systematic and future-oriented analyses of standardisation are needed at a policy level, involving a variety of stakeholders and SDOs with different technological and organisational perspectives. This is much more complex than strategic planning and management of standardisation at individual firms, as they would have different, or even conflicting, interests from each other (Betancourt & Walsh 1995; Branscomb & Kahin 1995). In addition, long-term perspectives are needed, considering where standardisation may serve as important public infrastructure, particularly in early stages of innovation where technology emerges from a science base. The current research thus focuses on frameworks and processes to help standards organisations and policymakers with long-term strategies for effective standardisation in support of overall innovation systems.

Third, as the current thesis focuses on developing a systematic framework that can also be used as a practical tool for standardisation foresight, it particularly draws on the structured and integrative approach of strategic roadmapping. From the exploratory review of academic literature and existing practices (details of which are further discussed in sections 2.4.5 and 4.1.3), it potentially provides a useful basis for the research by enabling the exploration of complex systems' evolutions, and providing a collaborative platform for various stakeholders to develop common strategies (Phaal et al. 2010; Muller 2016). Recognising such values, many countries have adopted roadmapping practices for effective management and foresight of standardisation, particularly in emerging technologies (e.g., NIST 2010; NPE 2012; DKE 2014). Yet, there are challenges for standards organisations and policymakers in structuring the framework and managing the overall process of developing it, because of its intrinsic limitations in addressing issues outside the system under consideration. In this regard, the current research attempts to develop more systematic and structured framework and process model based on the roadmapping approach, which can be used for understanding complex and dynamic interplays between standardisation and innovation, and aiding standardisation foresight in support of technological innovation. Further rationales for and benefits of the approach are discussed in section 4.1.

1.3 Research Questions

Having discussed the context and focus of the research, the overall research question of the current thesis is defined as follows:

How might complex dynamic interplays between standardisation and technological innovation be analysed systematically, and subsequently accounted for in strategic policy foresight?

Based on the above research question, there are five interrelated sub-questions:

- How might various roles and functions of standardisation in technological innovation be analysed systematically?
- What other elements and factors characterising standardisation need to be accounted for in analysing complex and dynamic interplays between standardisation and technological innovation?
- How can frameworks and processes for technology strategy be used to capture this information, allowing more systematic and future-oriented analyses for timely and effective standardisation in support of technological innovation?
- Do roadmap-based frameworks and processes offer particular opportunities for systematic and future-oriented analyses of standardisation in complex, multidisciplinary technological systems?
- What are the policy implications for using these frameworks and processes as strategic policy tools, particularly appropriate roles of government and other public agencies?

1.4 Research Approach

As there have been limited studies exploring standardisation and its strategic foresight in support of innovation from systems perspectives, the current thesis adopted a qualitative approach, in order to gain an in-depth understanding of phenomena that have not yet been well understood. Data were collected primarily from practice documents (over 450 documents) and semi-structured interviews (over 120 interviews, including preliminary interviews to define research questions), which were qualitatively analysed through within-case analyses, cross-case comparisons, and narrative analyses.

This research particularly aims at building theories from case studies, which is highly iterative and tightly linked to data. A conceptual framework and a process model for using it for standardisation foresight have been developed through four stages of research: (i) literature and practice review, (ii) multiple exploratory case studies, (iii) an in-depth case study, and (iv) verification interviews. Chapter 3 provides more detailed descriptions of the approach and methods adopted in each stage.

1.5 Potential Impacts of the Research

This thesis attempts to develop a systematic framework for standardisation in the context of technological innovation, and also a process model for using it as a practical policy tool for strategic foresight. The questions to be addressed by this thesis have both theoretical and practical relevance, which are discussed in this section.

By adopting more systematic and holistic perspectives on standardisation in broader contexts of innovation systems, the current thesis is expected to provide greater understanding of how standardisation supports technological innovation. It also aims to develop more systematic framework and process model based on the strategic roadmapping approach, by integrating important dimensions of standardisation identified in existing literature, particularly highlighting its technological complexities with detailed level of analysis.

With such new insights and understanding, the thesis is also expected to help standards organisations and policymakers make more informed decisions in standardisation foresight, ensuring effective and timely standardisation activities in support of their innovation systems. It aims to provide managerial implications of using the resulting framework and process model as policy tools, particularly appropriate roles of government in supporting standardisation and relevant strategic activities. It is hoped that the framework and process model can also make more general contributions to literature and practice of technology strategy, by providing more systematic structures and processes of strategic roadmapping.

1.6 Structure of this Thesis

This thesis consists of 8 chapters, as shown in Figure 1.1.

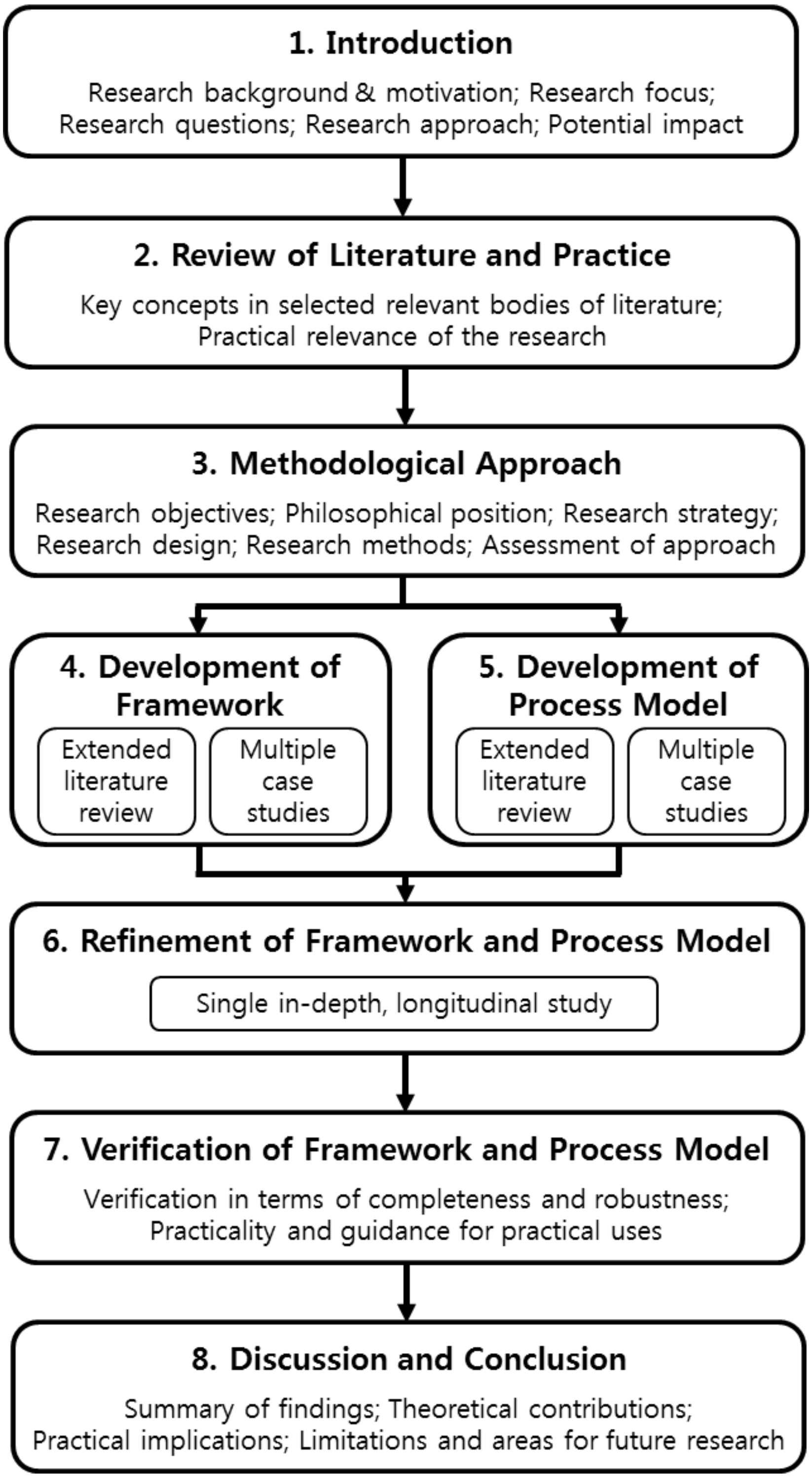


Figure 1.1 Structure of the thesis

The remaining 7 chapters are summarised as follows.

Chapter 2 presents an overview of relevant literature and practice regarding standardisation in the context of technological innovation. It provides theoretical and practical backgrounds of the research, helping define a research gap and refine research questions.

Chapter 3 presents the methodological approach adopted to address these research questions.

Chapter 4 presents a conceptual framework for systematic analyses of standardisation in the context of technological innovation, developed by a review of relevant literature and multiple exploratory case studies.

Chapter 5 presents a process model for using this framework for standardisation foresight, based on reviews of both literature and existing standardisation roadmapping exercises.

Chapter 6 presents more refined and targeted versions of the framework and process model, through an in-depth, longitudinal case study of photovoltaic (PV) technology.

Focusing on verification of the framework and process model, Chapter 7 discusses their robustness and completeness, as well as general practicality and guidance for using them in broader contexts, as suggested by various experts.

Drawing on results and discussions from previous chapters, Chapter 8 presents the summary of key findings (including the final framework and process model), its implications for theory and practice, limitations, and future areas of research.

2. REVIEW OF LITERATURE AND PRACTICE

This chapter presents the review of literature and practice relevant for standardisation in the context of technological innovation. Reviews of both academic studies and practice-oriented documents produced by standards organisations and public agencies are conducted, along with expert interviews to explore practical background and relevance of the research.

The general overview of existing literature on standardisation and innovation highlights needs for a more systematic and integrated approach to understanding their complex dynamics in broader contexts of innovation systems. Such needs may be partially addressed by the functions of innovation systems approach, which provides a useful basis for analysing various roles of standardisation in innovation from more systematic and dynamic perspectives. Although this approach is limited due to its high level of abstraction, it can be complemented by integrating more detailed aspects of their dynamics identified in existing frameworks. Needs for such systematic and integrative frameworks in practice are also discussed, followed by a brief review of existing practices adopted for standardisation foresight.

Based on the review, this chapter concludes by identifying a gap in both theory and practice. Rationales for the current research are thus justified, and its research questions are refined.

2.1 Backgrounds and Existing Studies on Standardisation and Innovation

2.1.1 Technological Innovation and Innovation Systems Approach

Often recognised as the core process of modern economic change and development, technological innovation generally refers to the implementation of new or significantly improved products and processes whose critical improvements rest largely on technological novelty (Dosi 1988; OECD 2005). As innovations are usually carried out through constant interactions and knowledge exchanges among various actors rather than 'in isolation', many scholars have recently adopted the systems approach to understand them (e.g., Van de Ven 1993; Nelson 1994; Edquist 2001). Providing a holistic, interdisciplinary, and evolutionary perspective of innovation (Edquist 2001; Smits & Kuhlmann 2004), this approach defines the innovation system as a set of "all important economic, social, political, organisational, and other factors that influence the development, diffusion, and use of innovations" (Edquist 1997, p.14). Thus highlighting interdependences and relationships between elements which make up innovation systems, this approach is useful for understanding the complex nature and dynamic processes of technological innovation.

There are a number of different types of systems approaches reported in the innovation literature, including national innovation systems (e.g., Freeman 1987; Lundvall 1992), regional innovation systems (e.g., Maskell 1996), sectoral innovation systems (e.g., Carlsson & Stankiewicz 1991; Malerba 2006), and a network approach to innovation systems (e.g., Håkansson 1987). Among these, this research particularly focuses on national innovation systems as the primary system level of the research, as they capture the importance of political and policy aspects of innovation processes, which are mostly concerned by policymakers and standards organisations (Edquist 2001).

2.1.2 Increasing Awareness of Importance of Standardisation in Innovation

The systems perspective on innovation has increased our recognition on the importance of standardisation in technological innovation. The gradual breakdown of linear models of technology development has led to greater interests in determinants of innovation systems, making standardisation more readily identifiable as an important variable in technological innovation (Hawkins et al. 1995; Edquist 2001). A number of academic literature on innovation systems note that standards are powerful institutional mechanisms that shape technological changes and direct innovations (e.g., Van de Ven 1993; Metcalfe & Miles 1994; Edquist 2001). Standards are also increasingly recognised in other academic and practice literature as effective channels for knowledge transfer and diffusion, along with other well-known channels of innovation, such as research collaboration, licensing, and personnel exchange (e.g., EXPRESS 2010). By codifying accumulated technological knowledge and best practice experiences, standards make information more accessible to various actors of innovation systems, supporting the dissemination of innovative ideas and new technologies (Allen & Sriram 2000; Blind & Gauch 2009; Swann 2010; Hogan et al. 2015). As the "activity of establishing and recording" these standards (de Vries 1999, p.13), standardisation is also recognised as a specific form of collaborative knowledge-sharing activities (Swann & Lambert 2010).

Such awareness of important roles and functions of standardisation in innovation is also due to the emergence of complex technological systems. They have reached an unprecedented level of complexity and universality (Lundvall 1995), requiring various types of standards – from production to process – covering a broad range of subjects, in order to precisely specify a large number of technical components (OCST 1993; European Commission 2011). The growing role of ICT also calls for a large infrastructure of 'pre-market entry' standards to achieve interoperability and data exchange (ISO/IEC 1990; Branscomb & Kahin 1995). In addition, the increasing requirements for interconnectivity and interoperability of systems due to the convergence of computing and communications have magnified the importance of standardisation in technological systems (Hawkins et al. 1995; Biddle et al. 2012).

2.1.3 Limitations of Exiting Literature on Standardisation and Innovation

Despite the increasing awareness of important roles of standardisation in technological innovation, existing literature have presented it in a less systematic and comprehensive way (Blind & Gauch 2009; EXPRESS 2010; Biddle et al. 2012). Previous academic research on standardisation generally focus on a particular technical discipline or a specific standard item (Cargill 1995; de Vries 2001). Their views on standardisation are also limited to certain aspects only, usually economic perspectives (Branscomb & Kahin 1995; Hawkins et al. 1995; de Vries 2001). In addition, most of them focus on theoretical studies, lacking empirical foundation and validation of the theory; there is very limited empirical evidence of impacts of standards on innovation, restricted to specific goods or markets only (Blind 2002; Blind 2013). Such limited analyses on the impact of standardisation are mainly due to many quantitatively non-ascertainable aspects of standards, that make it almost "impossible to analyse all the effects of standards in a comprehensive and holistic way," as noted by Blind (2004, p.183).

The lack of existing studies on comprehensive analyses of standardisation in broader context of innovation systems is mainly due to variations and confusion that are prevalent with standardisation, as can be seen from the broad use of the term 'standard'. Although the ISO (2004) definition – which defines a standard as "…a document, established by consensus and approved by a recognised body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context" – is the most commonly used, many academic scholars acknowledge that standards are defined in various different ways in different contexts, depending on various purposes and interests of various parties involved (e.g., de Vries 1999). Many standards organisations also tend to define more specific aims of standards that are fit for the purpose of their organisations (e.g., interworking and interchangeability objectives of standards as defined by CEN/CENELEC/ETSI).

Such variations and diversities involved in standardisation can also be observed from inconsistent classifications on dimensions of standardisation in existing literature. Although various academic and practical literature have been struggling to define its important elements and factors (e.g., Branscomb & Kahin 1995; Baskin et al. 1998; Sivan 1999), existing frameworks are neither consistent nor comprehensive enough to explicate complex and dynamic interplays between standardisation and technological innovation. Verman (1973) is one of the first in providing such efforts, suggesting a three-dimensional space as a way of describing and analysing the phenomenon of standardisation; whereas Sivan (1999) complements Verman's spatial approach, and proposes a more verbal framework composed of five dimensions of standards, i.e., level, purpose, effect, sponsor, and stage. Yet, both of them fail to capture high complexities and variations associated with innovation systems of complex technologies. In order to completely describe various domains of standardisation in the field of communications technology, Baskin et al. (1998) present a more systematic framework in terms of answers to six questions that are often used to describe any forms of human activity: what, why, when, how, who, and where. Despite its completeness and comprehensiveness, it only focuses on standardisation related to telecommunications.

In fact, there is a high degree of variety and complexity involved in standardisation, creating confusions in understanding its dynamics in the context of technological innovation. There are various forms of standards – e.g., product specifications, test methods, practices, and guidelines (ASTM 2012) – each playing different roles and functions (Allen & Sriram 2000;

Blind & Gauch 2009; Swann 2010), associated with varying levels of technical details (Tassey 2015; Muller 2016), and developed by a diverse mix of stakeholders with different interests (ASTM 2012; Muller 2016), all of which evolve over time along with technology development (Sherif 2001). They are also highly dependent on the dynamics of standardisation processes, composed of a variety of complex mechanisms; the outcome of standardisation depends on the path taken and past decisions, hence slight differences in past practices and procedures may produce very different results (Grindley 1995; Mansell 1995). In addition, as processes of innovation are characterised by a high level of risks and uncertainties, it is difficult to identify causal relationships between standardisation – i.e., inputs into the process – and their impacts on the final output (Blind 2013). Moreover, the intrinsic complexity and systems character of modern technologies also add significant challenges in precisely assessing roles and functions performed by standardisation in broad systems of innovation (Tassey 2000).

2.1.4 Needs for Systematic and Comprehensive Analyses

It seems that due to such complexities and varieties involved in both standardisation and technological innovation, previous studies have emphasised only certain facets or issues of standardisation, rather than examining its generic traits and functions in broader innovation systems with holistic perspectives. There are thus fragmented bodies of literature exploring standardisation in various domains and disciplines with different perspectives, such as natural science, engineering, law, economics, management, and policy studies (de Vries 1999; Lyytinen et al. 2008; Choi et al. 2011). From a systematic review of papers on technology standards, Narayanan & Chen (2012) also observe that scholars pursue this broad phenomenon from their own narrow disciplinary perspectives, adopting different levels of analysis and different ontological assumptions. Table 2.1 summarises how existing literature in various disciplines address different aspects, providing limited and only partial pictures of standardisation in the context of innovation. The lack of holistic and integrated studies results in limited understanding on overall dynamics of how standardisations actually spur innovation through various channels of knowledge transfer.

There is, however, an increasing awareness among academics that standardisation should be considered within a broader framework of technological innovation systems, considering many factors at once. Lundvall (1995) suggests that impacts of standardisation on various aspects of innovation, including economic, financial, environmental, cultural, social, and political spheres, need to be taken into account to a larger extent. Recognising complex processes and interactions involved in standardisation, Garcia et al. (2005) also propose to view standardisation in its entirety, to adequately assess its impacts and characterise its relationships with other innovation activities. Such an holistic and integrated approach to the complex issue of standardisation would provide a clear and accurate view of the problem domain, preventing fragmented and limited analyses of systems (Bonino & Spring 1999). Therefore, an integrative and systematic approach accounting for various aspects of standardisation is called for, providing greater insights and understanding for exactly what roles and functions they play to support broader systems of technological innovation.

Table 2.1 Overview of existing literature addressing various standardisation issues

Discipline	**Themes Relevant to Standards and Standardisation**	**Exemplar References**
Science and Technology	· Standards for knowledge transfer / diffusion · Standards as barriers to technological change · Types of technology elements associated with standards · (e.g., quality standards for component design, interface standards for connecting different systems) · Timing of standardisation relative to technology lifecycles	(Allen & Sriram 2000) (Brady 1933) (Tassey 2000; Bergholz et al. 2006) (Sherif 2001)
Economics	· Market rationales for standardisation (e.g., efficiency in transaction and trade, public good infrastructure) · Economic roles played by standards (e.g. network externalities, enabling economies of scale, providing information, increasing productivity)	(David 1987) (David & Greenstein 1990; Blind 2004)
Management	· Strategic management of standardisation by firms to gain market power · Asset ownership and control for standard wars · Dominant designs and de facto standards	(Betancourt & Walsh 1995) (Shapiro & Varian 1999) (Tushman & Rosenkopf 1992)
Sociology	· Standardisation as balance between flexibility and stability · Standardisation as coordination / collaboration activities among various actors	(Hanseth et al. 1996) (Grewal 2008)
Law	· Intellectual properties and ethical conflicts	(Biddle et al. 2012)
Standardisation Practice	· Various forms of standards · Various organisations developing standards · Management of standardisation activities	(ASTM 2012; Hatto 2013) (ASTM 2012; Hatto 2013) (ANSI 2014)

2.2 Functions of Standardisation in Technological Innovation

In order to analyse roles and functions of standardisation in technological innovation in a more comprehensive and integrative way, the 'functions of innovation systems approach' is adopted as a heuristic framework. As adopted by Walz (2007) in understanding the role of regulation in innovation systems, this approach offers appropriate linkages between diverse roles of standardisation in innovation, by analysing how different functions of innovation systems are influenced. This section introduces the functions approach, followed by detailed discussions of certain functions that are particularly relevant to standardisation.

2.2.1 Functions of Innovation Systems Approach

As the "determinants of innovations", functions are the relevant activities and key factors that influence the development, diffusion and use of innovations (Edquist 2001, p.3). Identifying and systematically mapping these functions help focus on the dynamics of what is actually happening in the system, providing insights into interactions of various elements and forces that determine the complex and evolutionary process of innovation systems (Hekkert et al. 2007). In addition, as it focuses on main activities being achieved in the overall innovation system, the functions approach can provide a more consistent perspective for making effective comparisons across various countries and technological domains, unlike other innovation systems approaches that focus on particular regions or sectors.

Various theoretical and empirical research have been carried out to identify a set of main functions that influence the performance of innovation systems, each associated with different issues and activities throughout innovation processes (e.g., Edquist & Johnson 1997; Smits & Kuhlmann 2004; Hekkert et al. 2007). Reviewing these earlier works, Bergek et al. (2008) propose the following list of seven functions that are synthesised from various approaches and further developed by them:

- *Knowledge development and diffusion*; is concerned with how new knowledge is developed from innovation system's current knowledge base and diffused to other activities. In order to avoid confusion with the general function of innovation that influence the development and diffusion of knowledge, the term ‘*creation and transfer of new knowledge*’ will be used instead throughout the rest of the thesis.

- *Influence on the direction of search*; covers mechanisms having an influence on the direction of search within the innovation system, among different competing technologies, applications, markets, business models, etc.
- *Entrepreneurial experimentation*; implies a probing into new technologies, applications, and markets, where a social learning process unfolds, reducing uncertainty throughout the evolution of innovation systems.
- *Market formation*; involves activities to support market evolution, from a nursing market where a learning space is opened up, to a bridging market where volume is increased, and finally to a mass market.
- *Legitimation*; is a matter of social acceptance and compliance with relevant institutions, so that new technology is considered appropriate and desirable by relevant actors in order for resources to be mobilised, demand to form, and actors to acquire political strength.
- *Resource mobilisation*; includes mobilisation of necessary resources, such as competence, human capital, financial capital, and complementary assets.
- *Development of positive externalities*; involves the generation of positive external economies, in the form of resolution of uncertainties, political power, pooled labour markets, combinatorial opportunities, and information/knowledge flows.

2.2.2 Functions of Standardisation in Support of Innovation Systems

By reviewing how standardisation is accounted for in literature adopting the functions approach, we can explore how it contributes to and interacts with the overall innovation system from a broader and more integrated perspective. Other literature discussing standardisation in the context of innovation are also reviewed, and their correspondences to the functions approach are identified for consistent analyses of various roles and functions of standardisation that are being achieved in supporting innovation systems.

In general, it can be observed that standardisation provides a generic function of innovation systems that influence the development and diffusion of knowledge. By codifying and transferring state-of-the-art technology and best practice among a variety of actors, standard publications support diffusion of technical knowledge developed throughout various stages of innovation systems (Allen & Sriram 2000; Swann 2010). In addition, the act of standardisation itself promotes knowledge development, as it provides a forum of collective cognitive processes where actors with heterogeneous backgrounds – i.e., research, industry, public administration, and users – are brought together to develop new ideas and solutions (Bergholz et al. 2006; Blind 2009; Hogan et al. 2015). As it involves discussions of such a variety of participants, standardisation process is also an effective channel of knowledge transfer and diffusion, where they can share best practice and state-of-the-art research based on their experiences (OCST 1993; Tassey 2000; CIE 2006; Blind 2009).

Table 2.2 summarises five functions of innovation systems that are specifically supported by standardisation, as discussed in various academic and practice literature; other functions are not directly referenced in existing literature. These are further elaborated as follows.

Table 2.2 Five functions of standardisation derived from the literature

Functions of standardisation	In innovation systems literature	In other literature on standardisation
Legitimation	· Reducing uncertainty by providing necessary information · Increasing social acceptance by managing conflicts	· Encouraging innovators to participate in innovation by reducing future uncertainty · Increasing consumer confidence, thus facilitating market access and allowing subsequent innovation
Influence on the direction of search	· Specifications and performance criteria to guide direction of learning · Powerful mechanisms for selecting dominant designs or specific technology	· Quality and performance standards to provide guidance on how to achieve target · Articulating demands from leading customers · Selection and prioritisation of certain technologies
Development of positive externalities	· Increasing the attractiveness for the customers through network effects · Economies of scale	· Variety-reduction standards for economies of scale · Compatibility and interface standards to generate positive network effects
Creation and transfer of new knowledge		· Providing an essential platform on which new innovations can emerge · Measurement and testing standards as a system of infratechnologies supporting R&D cooperation · Knowledge transfer channel by codifying R&D results and facilitating efficient communication
Entrepreneurial experimentation		· Promoting competition by levelling the playing field · Quality and performance standards to enhance competence building · Interoperability standards to promote products integration and their interactions

2.2.3 'Legitimation' Function of Standardisation

Many literature adopting the functions approach note 'legitimation' as one of the most important functions of standardisation. As a matter of social acceptance, legitimacy provides the new innovation system with appropriateness and desirability so that resources are mobilised and demand is formed (Bergek et al. 2008). Standardisation provides this legitimacy mainly in two ways. First, acting as signposts, they reduce social uncertainty and stimulate interactive learning activities by providing and communicating necessary information (Edquist & Johnson 1997). As high level of uncertainty accompanied by new innovations makes relevant actors reluctant to act towards innovative activities, standards that reduce such uncertainty are important prerequisites for new innovation systems to emerge (Lundvall 1992; Van de Ven 1993). Second, as an industry consensus process, standardisation provides legitimacy by managing and mitigating conflicts that may arise between different innovations or standards (Carlsson & Stankiewicz 1991).

Other literature also identify that standardisation increases the acceptance of, and confidence in, new technologies, facilitating market access and allowing subsequent innovation (Blind & Gauch 2009; Swann & Lambert 2010; European Commission 2011). It does so by reducing buyers' uncertainty about new products and services (Blind 2004; CIE 2006; Swann 2010), as well as reducing innovators' uncertainty about the future, so encouraging them to improve technologies (Foray 1998). There are various types of standards providing such legitimacy, including: quality and performance standards guaranteeing that products comply with minimum requirements (Blind 2004; Swann 2010), health and safety standards ensuring the compliance with applicable regulations (Hogan et al. 2015), and measurement standards enabling precision manufacture and demonstrating the superiority of products (Swann 2010).

2.2.4 'Influence on the Direction of Search' Function of Standardisation

Standardisation provides important functions of 'influence on the direction of search', by channelling entrepreneurial resources and other innovation activities towards particular directions. Setting standards pertaining to specifications and performance criteria – that new products or processes are expected to meet – have significant influences on guiding directions of search and learning activities (Edquist & Johnson 1997; Smith 1997). Standardisation is also a powerful mechanism for selecting dominant designs or specific technology areas from among competing possibilities, providing an important guidance in a technical sense (Lundvall 1992; Van de Ven 1993). In addition, standards influence behaviours of actors, by helping transmit information about what routines are acceptable and providing incentives for engaging in certain innovation activities (Smith 1997).

Such influences of standardisation on guiding innovation systems are also identified in other literature. Swann (2010) notes that quality and performance standards not only state a target level of quality, but also provide some direction on how to achieve that target level. According to Mansell (1995), technical design configurations embedded in ICT systems also have impacts on the direction of innovation; this is because they result in differential search costs of supply and use, which may influence information acquisition, leading innovation activities in certain directions (CIE 2006).

In addition, standardisation influences the direction of search by articulating demands from leading customers and making them readily accessible to all firms. Hogan et al. (2015) provide an example in the aerospace industry, where standards are used by manufacturers to effectively communicate their technical requirements to various suppliers. Bergholz et al. (2006) also acknowledge that the development task for equipment and materials manufacturers is well defined through standardisation of requirements from customers. Such selection and prioritisation of technologies may result in the bundling of resources which, in turn, performs the function of ‘resource mobilisation’ (Blind 2009).

2.2.5 ‘Development of Positive Externalities’ Function of Standardisation

Standardisation develops positive externalities in the form of network effects: benefits to users of a system rise with increasing number of users (Smith 1997). It may thus increase the attractiveness for customers, leading to rapid diffusion of new innovation systems (Edquist 1997). Such network externalities encourage innovation actors to participate in other functional activities such as ‘creation and transfer of new knowledge’ and ‘market formation’, strengthening the overall functionality of the system (Bergek et al. 2008). On the other hand, an absence of similarity standards may lead to a fragmented market lacking critical mass to achieve economies of scale, thus blocking the ‘market formation’ function of innovation (Bergek et al. 2008).

Other literature on standardisation also suggests its important role in providing the ‘development of positive externalities’ function in various ways. Variety-reduction standards foster the diffusion of new products and technologies, by allowing the exploitation of economies of scale (Blind & Gauch 2009). Measurement standards also help to develop economies of scale by enabling advances in process control (Swann 2010). In addition, compatibility and interface standards generate positive network externalities by establishing successful linkages between various components and products; these allow more actors to join the innovation system, contributing to the functions of ‘creation of new knowledge’ and ‘entrepreneurial experimentation’ (CIE 2006; Blind & Gauch 2009; Swann 2010; Hogan et al. 2015). Such network externalities also occur during the production; the reduced variability of manufacturing processes facilitates the industrial learning curve, as the technology improves with the accumulation of experience with its use (Bergholz et al. 2006).

2.2.6 ‘Creation and Transfer of New Knowledge’ Function of Standardisation

Although the ‘creation and transfer of new knowledge’ function of standardisation has not been highlighted much in innovation systems literature, it is an important function that is discussed the most in other standards-related literature.

As a widely-agreed, accepted, and implemented baseline of accumulated technological experience, standardisation provides an essential platform on which new technical knowledge can be created, supporting new innovations to emerge (Hawkins et al. 1995; Allen & Sriram 2000; CIE 2006; Blind 2009). For example, by establishing common understanding of basic elements of new technologies, terminology standards provide the basis of research (Blind & Gauch 2009). Similarly, interoperability standards for mobile services act as platform for various mobile commerce solutions (European Commission 2011).

In addition, standards allow transfer and diffusion of new knowledge, by codifying results of private or publicly funded R&D and making them available to the public, so bridging the gap between research and other stages of innovation (Blind 2002; Blind 2009; European Commission 2011). For example, by facilitating efficient communication among researchers investigating new technologies, terminology standards transfer knowledge from basic to oriented-basic and applied researchers (Blind & Gauch 2009). Similarly, measurement and testing methods for quality and safety support conversion of new knowledge from scientific research into market, bridging the gap between research and marketable products or services (CIE 2006; European Commission 2011). Such standards also promote the transfer of new technologies and innovative products, enhancing the 'market formation' functional activities (Foray 1998; European Commission 2011; Hogan et al. 2015).

2.2.7 'Entrepreneurial Experimentation' Function of Standardisation

The 'entrepreneurial experimentation' function of standardisation is not widely discussed, but is noted by some standardisation literature as indirect methods of spurring innovation by promoting competition (Allen & Sriram 2000). By specifying a minimum level of performance, quality and performance standards enhance competence building as businesses try to enhance the quality of their products and the process efficiency (Tassey 2000; Swann 2010). Some academics claim that standardisation also provides a point of departure for competition by levelling the playing field (Blind 2009; Hogan et al. 2015). In addition, compatibility and interoperability standards promote development of new products and processes by facilitating interactions among different technologies, thus creating the environment for new experiments where they can be integrated into innovative systems (Blind & Gauch 2009; Blind 2009; Hogan et al. 2015).

2.2.8 Discussion on Functions of Innovation Systems Approach

As discussed above, the functions approach provides a more systematic, dynamic, and comprehensive perspective of how standardisation influences the overall innovation system. The review of literature reveals that standardisation provides important functions of 'legitimation', 'influence on the direction of search', 'development of positive externalities', 'creation and transfer of new knowledge', and 'entrepreneurial experimentation'.

It is also highlighted by adopting the functions approach that standardisation 'mediates' between various functions of innovation systems, supporting overall innovation. By codifying accumulated technological knowledge and helping transmit this knowledge among a variety of innovation actors, published documents of standards facilitate interactions and interplays between various innovation activities and functions. For example, measurement and testing standards support R&D cooperation through cumulative learning, and allow exchange and mutual evaluation of the experimental results (ISO/IEC 1990; Foray 1998; Blind & Gauch 2009; Swann 2010). Compatibility and interface standards also create the environment for knowledge development of various stakeholders, by facilitating interactions among products and processes supplied by different firms (Hogan et al. 2015). In addition, the act of developing standards provides important grounds of knowledge development and diffusion for innovation actors, by sharing and exchanging the latest technical information (Foray 1998; Bergholz et al. 2006; Swann & Lambert 2010). Such 'mediating' roles of standardisation by linking various innovation activities and functions enhance the overall functional dynamics of innovation systems, expediting innovation processes and promoting further innovation.

However, trying to incorporate too many factors at once, the functions of innovation systems approach is at a very abstract level. As innovation is a complex interplay of various activities having significant influences on each other, it is difficult to make clear distinctions or boundaries between different functions. It is thus challenging to observe real impacts of individual standardisation activities on innovation systems, as they are often described in an aggregated form. In addition, it does not provide detailed information on various dimensions of standardisation – such as different types of standards and various stakeholders involved – and their interactions with other innovation activities. Such lack of information makes it difficult to thoroughly understand complex and dynamic interplays between standardisation and technological innovation, increasing challenges in strategy development for timely and effective standardisation. Therefore, building on systematic and dynamic perspectives of the functions approach, a more precise and comprehensive framework capturing various dimensions of standardisation is required, for more detailed elaborations of how standardisation supports innovation.

2.3 Existing Frameworks for Standardisation in Support of Innovation

There have been a few scholarly attempts to establish frameworks representing more detailed characteristics of complex dynamics and interactions between standardisation and other innovation activities; integrating various aspects and issues identified by them may complement the high level of abstraction of the innovation systems functions approach. This section discusses three frameworks that provide particularly useful insights into the complex and dynamic interactions between standardisation and innovation.

2.3.1 Various Functions of Standardisation with Relevant Technology-Based Activities

Tassey (2000) is one of the earliest scholars to construct a framework for various types of standards (both product and nonproduct) and their economic functions in technology-based industries (see Figure 2.1). Recognising the complexity and systems character of modern technologies, his framework clearly represents that different types of technology (including generic technologies, infratechnologies, and proprietary technologies) have distinct characters, so requiring different types and combinations of standardisation for different activities of overall industrial systems (including R&D, production, and market penetration). He also discusses how these standards have significant collective effects on innovation, productivity, and market structure, thus emphasising needs for different formulation and implementation strategies (e.g., degrees of standardisation).

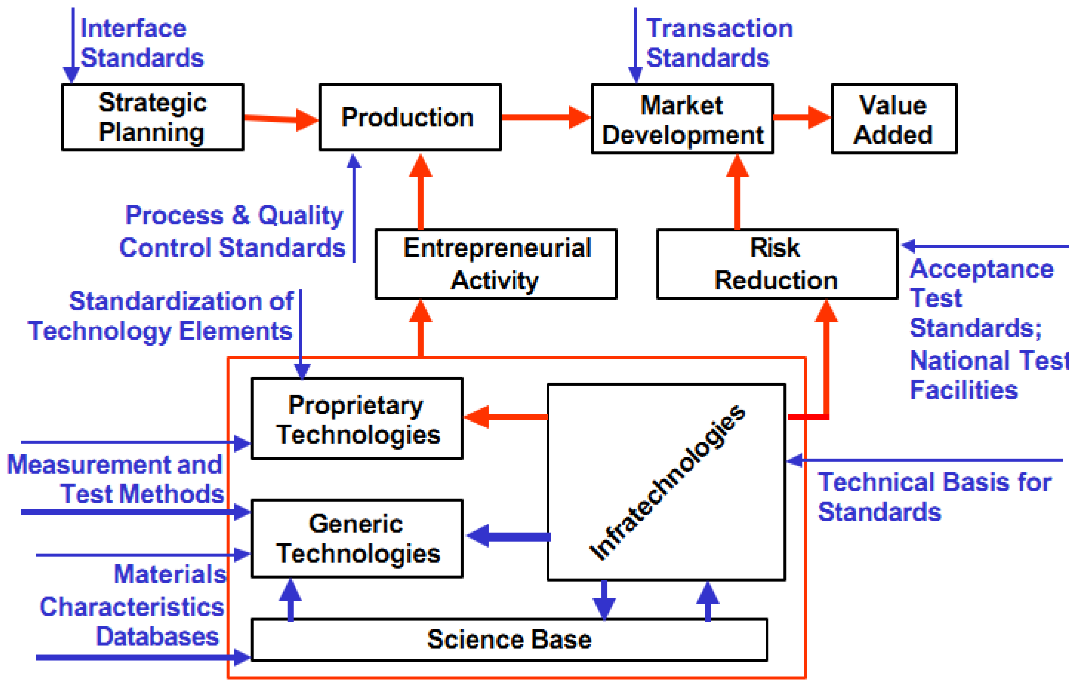


Figure 2.1 Various functions of standards in technology-based activities (Tassey 2000, p.589)

2.3.2 Standardisation Relative to the Technology Lifecycle

Focusing on standards relevant to ICT, Sherif (2001) has proposed a framework relating different categories of standardisation with technology lifecycles – often referred to as S-curves – and discusses how they are associated with different types of technology systems, playing different roles (see Figure 2.2). According to his framework, anticipatory standards are at the introduction of new technology, specifying production systems of the new technology, such as definitions of new concepts, features, and tools needed to proceed with trial implementations. Participatory standards follow as the performance improves and knowledge of the technology is diffused, for refinements in product systems or specifications for behaviours of application systems. Finally, towards the end of the technology lifecycle, responsive standards related to the manifestation of the technology in service systems appear, ensuring operation of completed and connected set of transformational technology systems. The framework thus emphasises the importance of appropriate strategic decisions (e.g., timing of standardisation) for different types of systems (i.e., production, product or application, and service) associated with a single technology at different stages of its lifecycle.

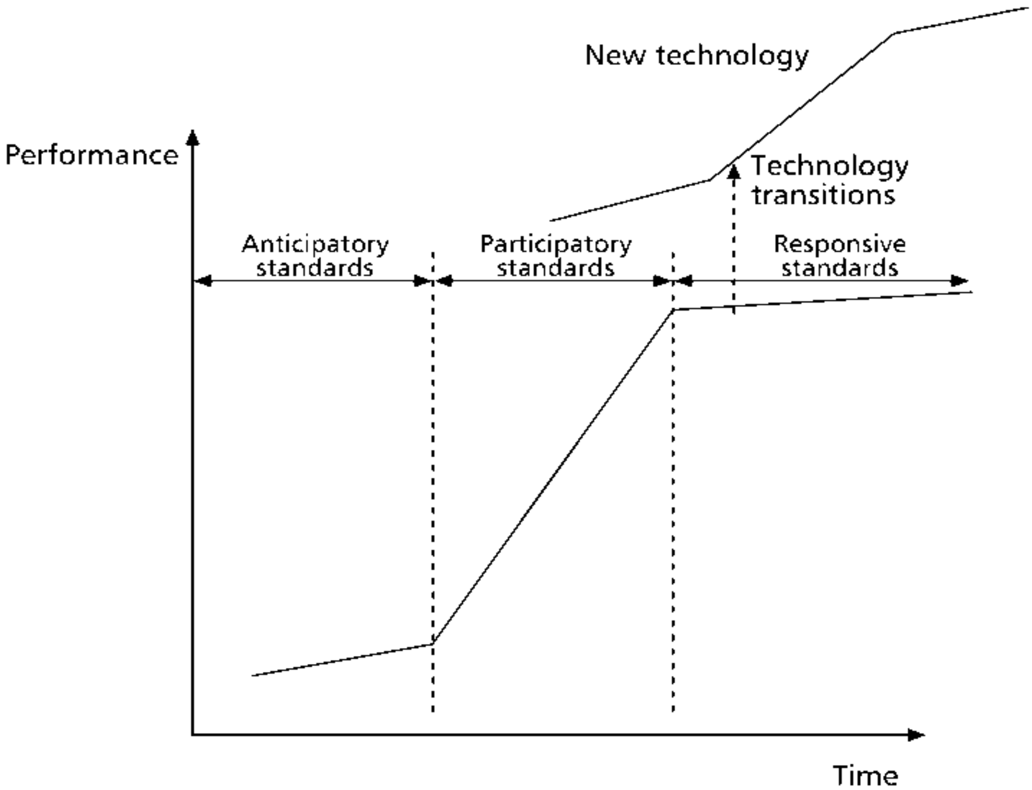


Figure 2.2 Standards in relation with the technology lifecycle (Sherif 2001, p.97)

2.3.3 Functions of Standardisation in Innovation Processes

A more recent framework is developed by Blind & Gauch (2009), showing various functions of standardisation in technological innovation and development, in addition to their general economic functions in the market (see Figure 2.3). Identifying standardisation as important channels of technology transfer in research and innovation, it distinguishes various roles of different types of standards at different phases of the innovation process (based on its linear model) from basic research to technology diffusion. Highlighting constant interactions within and between different stages of innovation processes as multiple feedback loops, it suggests that different types of codified knowledge are transferred by different standardisation at different phases of an (single) innovation project.

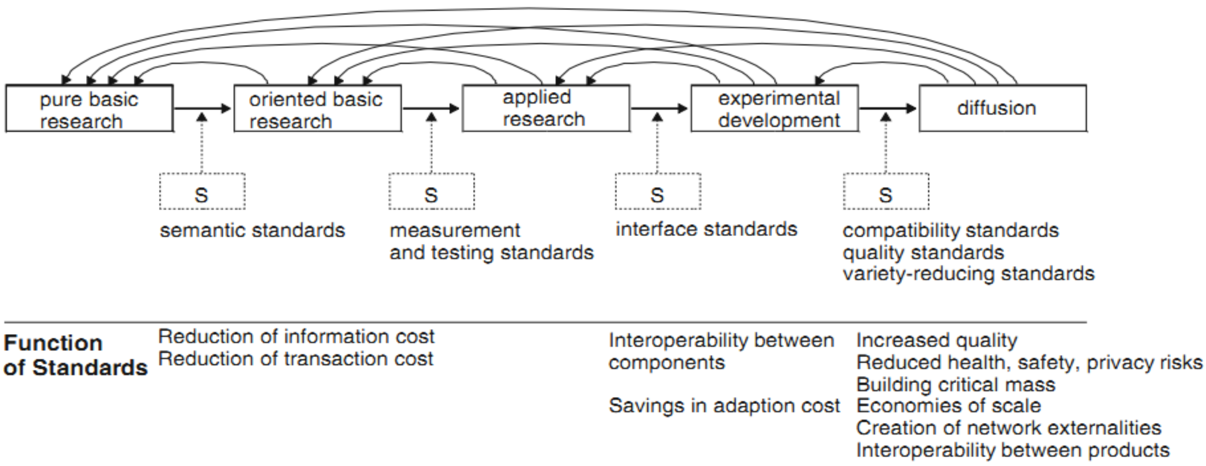


Figure 2.3 Various types of standards in the innovation process (Blind & Gauch 2009, p.325)

2.3.4 Discussion on Existing Frameworks for Standardisation and Innovation

Three existing frameworks provide conceptual models with a more detailed level of analysis, capturing various roles and functions of standardisation, as well as their dynamics with different innovation activities at different stages of technological innovation. They thus allow more thorough and precise understanding of how standardisation supports technological innovation, complementing the holistic, yet abstract approach of the innovation systems functions.

However, each framework addresses only certain aspects or characteristics of standardisation in the context of technological innovation, providing partial pictures of their complex dynamics (see Table 2.3 for details). Although they all highlight various roles and functions of innovation systems provided by different types of standards, not all of them are addressed in frameworks developed by Tassey (2000) and Sherif (2001), thus lacking completeness in analysing their dynamics. In addition, focusing on different levels of systems complexity and lifecycles, each framework is appropriate for only certain perspectives of innovation systems (i.e., single project, technology, or industrial system), as opposed to complex systems of modern technologies consisting of multiple innovations and diverse technological domains. Such lack of coherence and comprehensiveness results in limited perspectives for government or standards organisations to develop effective strategies for standardisation in support of broader, overall innovation systems.

Therefore, a more comprehensive and holistic framework capturing all relevant issues of standardisation with extended, long-term perspectives is needed, for complete and coherent analyses of its complex dynamics and interactions with technological innovation. The systematic integration of various dimensions of standardisation identified in these existing frameworks, by adopting the holistic and integrative approach of the innovation systems perspective, will provide greater insights and understanding of standardisation in support of innovation. This will help more effective management of standardisation at a policy level, improving the exploitation of technological innovation and its transition into the market, thus increasing industrial competitiveness (European Commission 2011).

Table 2.3 Different characteristics and issues addressed in existing frameworks

	Tassey (2000)	**Sherif (2001)**	**Blind & Gauch (2009)**
Major issues / themes (identified in section 2.1.4)			
- Technology elements / systems	√	√	
- Other aspects of innovation (e.g. market, law)	√		√
- Roles / functions (types) of standardisation	√	√	√
- Timing / sequencing of standardisation		√	√
Functions of innovation systems (see section 2.2)			
- Legitimation	√		√
- Influence on the direction of search	√		√
- Development of positive externalities	√	√	√
- Creation and transfer of new knowledge	√	√	√
- Entrepreneurial experimentation			√
Focusing lifecycle	Industrial system	Technology	Innovation (project)

2.4 Strategic Management and Foresight for Standardisation at a Policy Level

This section explores practical relevance of the research, by reviewing existing literature (both academic and practice-oriented literature) and practice. The practice review includes desk-based research of existing policy practices using documentations, as well as engagements with the practitioners' community through participant observation and preliminary interviews. Thirty-four experts from various organisations (e.g., government, SDOs, research laboratories, and academia) of different countries (e.g., UK, Germany, US, and Korea) provided useful insights into this review, bringing various perspectives and experiences in standardisation (e.g., strategic management of standardisation in SDOs, development of standards in technical committees, and academic research in standardisation); see Table A.1 in Appendix A for their profiles.

2.4.1 Increasing Attention on Importance of Standardisation at a Policy Level

Although standardisation had been recognised as an important factor of a nation's technological pre-eminence by providing a head start in innovation and development (Garcia 1993), there were remarkably little literature on standardisation from a policy perspective, as it was generally considered to rely solely on market forces (Branscomb & Kahin 1995; Mansell 1995). Existing literature on economics of standardisation discussed some important implications for policy – e.g., problems of market fragmentation and stranding of users with poor standards – and identified potential needs for public interventions to avoid such problems (e.g., Farrell & Saloner 1986; David 1987), but only limited influence was suggested for government as it is highly imperfect (Grindley 1995). Government's involvement in standardisation was thus often indirect, only in cases where there were special opportunities in achieving harmonisation, such as issues of tariff and network use (OTA 1992; Mansell 1995), or in some of the key areas with public and societal policy objectives, including health and safety, and environmental protection (Libicki et al. 2000; EXPRESS 2010).

Towards the late 20th century, the observation of powerful network effects and externalities in an information-based global economy allowed public sectors to become aware of the importance of standards; they could not only be employed strategically as marketing tools, but also act as a basic infrastructure for economic growth and development, according to many interviewees and literature (e.g., Branscomb & Kahin 1995; Garcia 1993). In such a networked information society, standardisation has been critical for interoperability, providing an open platform to support all economic, political, and cultural activities; thus government had greater interests in articulating a coherent vision of standardisation and how they relate to its fundamental societal value, such as national security and intellectual property (OTA 1992; European Commission 2011). In addition, it was an important 'public goods' infrastructure – i.e., goods whose benefits are available to everyone and from which no one can be excluded – in a society with strong network effects (Kindleberger 1983; OTA 1992). As such public goods might be typically under produced and subject to considerable market and system failures (Kindleberger 1983; Tassey 2005), needs for an active role of government and public policy in standardisation have been recognised to address these problems (Katz & Shapiro 1985; OTA 1992).

Realising such public interests for more effective standardisation, many governments have incorporated relevant strategies into policy programs (Hawkins et al. 1995). Japan was one of the first to use standardisation as a key component of industrial policy to improve economic efficiency and promote trade; standardisation also played a central role in the European policy for unification and industrial development (Garcia 1993). However, the focus mostly remained in economic aspects of standardisation only, such as maximising efficiency in trade and network externalities of interoperability, not addressing broader innovation systems (Branscomb & Kahin 1995)

The importance of standardisation at a policy level is recently gaining more attention, as studies – both theoretical and practical – show that standards not only have positive impacts on economic growths by promoting operational productivity and trade efficiency, but also act as important channels of knowledge diffusion supporting national innovation systems (e.g., Hogan et al. 2015, also see sections 2.1 and 2.2). In addition, there are increased challenges and urgency for standardisation of ever expanding technological systems, in order to promote their industrialisation and capture greater value from complex supply chains (further discussed in section 2.4.3). Many public organisations across the world are thus recently introducing effective standardisation as an important policy instrument to support their innovation systems (e.g., CSTP 2010; European Commission 2011), along with traditional, less systematic policy instruments, such as financial supports for R&D (Smits & Kuhlmann 2004).

2.4.2 Needs for Strategic Management and Foresight for Standardisation

Despite the increasing awareness of their critical roles in supporting innovation in both theory and practice, there had been prevailing perceptions that standardisation inhibits innovation by limiting variability and flexibility. In early studies of standardisation, Brady (1933) emphasised the relatively fixed and changeless nature of standards in technology and industry, representing stability, order, and regularity, in contrast with the dynamic, revolutionary, and stimulating power of technological change. Using an economic model, Farrell & Saloner (1986) argued how installed-base effects may create a bias against new technology, potentially inhibiting innovation. Other literature also discussed how premature standardisation – i.e., standards established before technology reaches its full potential – or even standards which are technologically advanced when it first appeared may hold up further innovation when they become technically obsolete (Grindley 1995).

In fact, the effect of standardisation on innovation largely depends on its timing. A standard that is imposed too early forestalls diversity and precludes entrepreneurial experiences, closing opportunities for further technological improvement and promising innovation, as often discussed with the case of QWERTY keyboard (David 1987; CIE 2006). On the other hand, a standard that comes along too late may retard achieving economies of scale for new market development, resulting in unnecessary costs of duplication and market confusion, both of which are potentially detrimental to innovation (Foray 1998; CIE 2006). Standardisation is thus a complex dynamic optimisation problem to balance between flexibility and stability (Lehr 1995). Moreover, as outdated standards may also impede changes and threaten innovation by locking into inferior legacy systems, update of standards in a timely manner is critical (Blind 2004). Yet, because initial standards, particularly the ones providing interoperability, may be hard to modify due to installed-base effects, a well organised change management process is necessary for the effective update of standards (Branscomb & Kahin 1995; Bergholz et al. 2006).

There are also some other cases where standardisation may have negative impacts on innovation. Competing standards decrease overall interoperability, resulting in fragmented markets and less technology diffusion; such problem is acerbated as standards evolve over time with technology development, increasing systems complexity and leading to performance degradation (Egyedi 2012). Standardisation may also involve risks of monopoly, creating market structures with a low level of competition, especially in network industries where standardisation can act as a technological bottleneck (Blind 2009). In addition, Maxwell (1998) argues how minimum quality standards may inhibit welfare enhancing innovation, by reducing firm incentives to innovate. In order to avoid such negative impacts of standardisation to innovation, they need to be planned and managed in a more strategic way (ISO/IEC 1990).

In summary, standards can be either beneficial or hindrance to innovation, depending on how and when they are developed, implemented, and managed. Strategic management and planning for standardisation to develop appropriate standards (with right content and flexibility) and implement them in a timely manner are thus crucial (Branscomb & Kahin 1995). This actually contrasts with the existing paradigm, where there was no serious planning and management of standardisation, due to an implied intuitive understanding that standards are written only after they are decided by the market (Cargill 1995). However, reactive approaches to standardisation seem to be no longer competitive, and needs for systematic and future-oriented analyses to effectively support innovation are gaining great attention, according to many practitioners. Such analyses requires foresight, which refers to a systematic "process of creating an understanding and application of information generated by looking ahead… to meet the needs and opportunities of the future (Coates 1985, p.343)." Helping to cope with the complexity and uncertainty associated with the future, foresight is increasingly used to support decision-making processes in policy or strategy development (Martin & Irvine 1989; Saritas & Oner 2004; Georghiou et al. 2008).

2.4.3 Increased Challenges and Roles of Government in Standardisation Strategies

The problem of planning and managing standardisation requires concurrent engineering and dynamic system processes involving various activities of a diverse group of actors, including SDOs, industry consortia, government policymakers, regulators, and implementers (Branscomb & Kahin 1995). Aikin & Cavallini (1995, p.254) also notes that "only by using a combination of various standards… at different levels of maturity and from different SDOs," can standardisation effectively support innovation. This is generally difficult, because standardisation requires many years of efforts due to continuous arguments and delays to reach consensus, thus increasing their vulnerability to unpredictable events (Morell & Steward 1995). It is also because standardisation often requires technical knowledge with different technological bases from that of core technology (Tassey 2000). It is noted by many literature and interviewees that strategic management and foresight of standardisation is currently faced with even greater challenges due to recent trends in modern technologies; these challenges are discussed as follows.

First of all, the increasing complexity of technologies involved in various products and systems requires a large number of high-quality standards with increasing level of technical details and sophistications. In particular, the systems nature of modern technologies has increased the number and variety of standards needed, due to the high number of interfaces between different components and systems (Tassey 2000; Tassey 2015). Along with the trend towards global high-tech corporate networks – characterised by the distribution of R&D and production among suppliers, manufacturers, and service providers across geographic borders –, it has resulted in a large infrastructure of standards needed to exchange data between networked participants and to reduce associated transaction costs (Ernst 2009; Tassey 2015). Most of these standards are also interrelated to and influenced by each other, having greater impacts on the evolutionary development of overall technological systems, noted multiple interviewees; hence, more careful planning and management of standardisation is needed.

The challenges associated with the systems-nature of technologies are even more increasing, as modern systems are interdisciplinary and heterogeneous, involving different industry sectors with different technology platforms and building-blocks, which formerly had distinct markets (Branscomb & Kahin 1995; Ernst 2009; Jakobs et al. 2011). The integration of various technologies and the increasing importance of ICT in many industrial domains may generate relationships among standardisation that did not exist before, thus requiring the coordinated engagement of a vast range of activities among actors with different backgrounds and disciplines (Morell & Steward 1995). Coordination among various stakeholders involved in standardisation is extremely challenging, as noted by multiple interviewees and existing studies (e.g., Morell & Steward 1995). These are becoming even more significant, as some of them have been working in different forums under different rules and cultures, which may create confusion and culture clashes when different standardisation paradigms collide (Biddle et al. 2012). For example, standardisation of electromobility requires coordinating and integrating diverse activities in the domains of electrical engineering, ICT, and automotive technology, whose standardisation used to be viewed as separate activities (NPE 2012).

In addition, there are increasing pressures from the growing speed of technological advance (Blumenthal & Clark 1995; Tassey 2015). As the average technology lifecycle is becoming shorter, standards are often proved to lag behind rapidly evolving technologies, noted many interviewees; they sometimes become even obsolete when eventually adopted, because of the lengthy procedures of development and implementation (European Commission 1996). This becomes increasingly problematic as many technologies merge with ICT, whose product and service lifecycles are known to be relatively short, not to mention their requirements for anticipatory standards to achieve interoperability. Experts from standards organisations as well as academia thus highlight that the reactive approach to standardisation is no longer appropriate in fast-evolving technologies, calling for more anticipatory and timely standardisation.

Last but not least, the issue of anticipation and early adoption of standards has gained increased attention in public policy, as the current society heavily relies on complex systems of networking and information technologies, where interoperability standards are more essential than ever for a nation's security, environment, and quality of life, noted multiple interviewees. Identifying future standardisation needs in a timely manner and developing relevant long-term strategies are thus important policy interests across the world (Goluchowicz & Blind 2011). Many governments actually identify planning and coordinating standardisation activities as critical national priorities, particularly in ICT-enabled, complex, and interdisciplinary areas, such as smart grid (NSTC 2011).

The increasing challenges – due to the fast pace of technological development, the increasing complexity of technological systems, and the technological and industrial convergence which require coordination of stakeholders from diverse domains – yet higher public interests of standardisation all call for more coherent leadership by government or other public agencies. In addition, the increasing complexity of standardisation work itself entails higher costs, so requiring active involvement of government to avoid the public good problem (Lundvall 1995). Many academics and practitioners thus identify needs for a strategic policy tool to support standardisation with proactive foresight measures (Branscomb & Kahin 1995;

Moreton 1999). This includes general policy foresight with standards-related issues framed within a broader context of innovation systems (e.g., setting priorities on areas that require public R&D to develop necessary standards infrastructure), as well as more specific standardisation foresight in particular technological systems (e.g., anticipating particular standardisation needs, and adjusting the existing stock of standards to keep up with the state-of-the-art technology) (Blind 2004). Multiple interviewees particularly noted increased challenges with selection and alignment of SDOs to provide necessary standardisation solutions, as their activities and expertise often overlap with each other.

2.4.4 Required Characteristics of a Systematic Approach to Standardisation Strategies

In order to address challenges identified in the previous section, it appears that a more systematic, integrated, and future-oriented approach to standardisation strategies is needed, with the following characteristics.

As standardisation is a dialog about technology and how codification of its common implementations may enable knowledge transfer and spur innovation (Branscomb & Kahin 1995), standardisation strategy that is closer to technical R&D may help keep abreast of the higher speed of technological change, noted many interviewees. More closely guided by the current state of science and technology, it may not only ensure that standards are based on sound research results, but also promote efficient transfer of innovative ideas through standardisation (European Commission 1996; Blind 2004). The European Commission (2011, p.7) also emphasises the need for "a systematic approach to research, innovation and standardisation… to improve the exploitation of research results, help best ideas to reach the market and achieve wide market uptake." Such systematic approach to research and standardisation is especially critical if standardisation is to be used as a strategic means of stimulating innovation and promoting dissemination of innovative ideas.

With the increasing systems character and rapid development of today's technologies, the systematic approach to standardisation strategy also requires detailed analyses on structural characteristics of overall technological systems. For complex systems with new technologies continuously being introduced into ever expanding systems, having a structural view of the overall systems architecture with hierarchical layers helps understand how all products and systems are interconnected to each other, identifying various interfaces at different levels where standardisation can help link them together. As all these system elements evolve at different rates and thus need updated interfaces and specifications at different points in time, their architectural views are also needed for more effective management of standardisation under the dynamic pressure of the evolution of technology systems (Tassey 2015). Such analyses are particularly important in ICT-related systems, which consist of a vast number of interfaces where standards are required for efficient data processing and communications within and between various networks. In addition, systematic analyses of systems architectures help set coherent long-term directions among diverse stakeholders from various disciplines (Blumenthal & Clark 1995).

Although actual development of standards mainly involves highly sophisticated technical work, standardisation is also subject to many other factors of innovation over which it has little or no control – including the advent of new technologies, national industrial policy, and market competitions – as noted by multiple interviewees as well as existing literature (e.g., Morell & Steward 1995). Such external forces and dynamics have unpredictable, but potentially large impacts on standardisation, so various activities in broader innovation systems – including technology, market, and public policy – and their dynamic interplays need to be considered in a more holistic way, in order to deal with high uncertainties and complexities associated with standardisation. It thus appears that these various perspectives, in addition to details of technological systems, need to be integrated in a more concurrent manner for effective standardisation foresight.

In order to develop standardisation strategies that account for various aspects of innovation systems and is coherent with a complete national strategy for innovation, its development should involve participation of a broader group of experts with different interests and backgrounds. This includes not just researchers in science and technology, but also industry consortia, policymakers from various departments, regulators, as well as public organisations representing users and consumers (e.g., EXPRESS 2010; Goluchowicz & Blind 2011). Multiple interviewees from different organisations also note that cooperation and coordination of these various stakeholders are essential for effective and timely standardisation in support of technological innovation.

In summary, a systematic approach, which not only considers complexities and diversities involved in technological innovation in detail, but also allows coordinated engagement of various stakeholders involved, is needed to address challenges with standardisation strategies.

2.4.5 Recent Policy Efforts for Standardisation Foresight

Recognising its importance, there is an increasing awareness of the needs for a systematic and future-oriented approach to standardisation in support of technological innovation, according to many experts and policy studies (e.g., European Commission 2011; Scapolo et al. 2014). In particular, standards organisations and policymakers note the potential value of robust frameworks and foresight processes for anticipating future standardisation needs, by linking them with research and other innovation activities within a broader strategic framework (European Commission 2011; Scapolo et al. 2014). Accordingly, there have been a number of efforts to carry out such strategic foresight analyses in practice, especially in emerging technology areas, for effective anticipation and management of standardisation.

For example, the US' National Institute of Standards and Technology (NIST) developed a number of conceptual frameworks and roadmaps for coordinating standardisation activities in various domains with standards-related opportunities, including smart grid, cloud computing, and additive manufacturing (NIST 2010; Hogan et al. 2011; NIST 2013). SDOs in Germany adopted the roadmapping approach as a way of anticipating future standardisation needs in a variety of interdisciplinary areas, such as electric vehicles and smart manufacturing (NPE 2012; DKE 2014). SASAM (2014) also developed a standardisation roadmap in the field of additive manufacturing, focusing on identification of necessary standards and formulation of strategies to develop them, to support the additive manufacturing industry through strategic management of standardisation. The EU 'Towards a European Strategy in Synthetic Biology' (TESSY) project offers another example in which special attention is paid to strategic standardisation as an effective policy support for an emerging area of synthetic biology (TESSY 2008).

From the review of existing practices, it appears that standardisation roadmap is one of the most widely adopted policy tools for supporting strategic management and foresight of standardisation, providing systematic and future-oriented perspectives for planning and developing standardisation strategies in an appropriate and timely manner. Standards organisations in many countries have developed standardisation roadmaps in various technological and industrial domains where effective management of standardisation is of strategic national importance, especially in emerging interdisciplinary areas. Interviewees who participated in developing such roadmaps note that roadmapping activities lead to more aligned and harmonised standardisation activities, by providing a platform for communication and collaboration of various stakeholders from different backgrounds, which are critical for effective and timely standardisation.

Despite its increasing popularity, current understanding of systematic foresight exercises for standardisation – including roadmapping – are somewhat limited, leaving substantial challenges for policymakers and standards organisations when adopting the approach. In fact, there has been little academic literature addressing issues of anticipation or foresight for strategic management of standardisation from a public policy perspective. A notable exception is the work by Goluchowicz & Blind (2011), discussing their experiences of applying Delphi studies for identifying future fields of standardisation. There is thus a lack of comprehensive and systematic considerations of various factors that need to be accounted for in such foresight exercises that aim to anticipate future standardisation needs and develop relevant strategies.

2.5 Identifying a Research Gap

Despite the growing awareness of standardisation as important channels of knowledge transfer and diffusion, there are fragmented bodies of literature exploring it from different disciplinary perspectives, resulting in limited and less comprehensive views on its complex dynamics in broader systems of technological innovation. Providing dynamic and holistic perspectives of what activities are being carried out in innovation systems, the functions of innovation systems approach is useful in observing how standardisation contributes to overall innovation systems in broader contexts. However, its high level of abstraction and aggregation make it difficult to observe the real impacts of individual standardisation activities on technological innovation, thus a more practical analytic framework is needed for detailed analyses of complex dynamics and interactions between them. Although there is a number of existing frameworks representing these dynamics in detail (e.g., Tassey 2000;

Sherif 2001; Blind & Gauch 2009), they emphasise only certain aspects and issues of standardisation, with focus on different levels of systems complexity and lifecycles. They are thus neither complete themselves nor consistent from each other, providing limited pictures of complex interplays and interdependencies between standardisation and other aspects of innovation. Therefore, a holistic and integrative conceptual framework with long-term perspectives is needed, systematically capturing all dimensions of standardisation in the context of technological innovation with detailed levels of analysis.

Further review of literature and practice reveals that there are also increasing needs for strategic management and foresight of standardisation, because of its importance as critical public infrastructure, as well as its dual impact – supporting and inhibiting – on innovation. In addition, recent trends in modern technologies becoming more complex, fast-evolving, and systems in nature impose significant challenges, with increasing roles of government in providing coherent, long-term leadership for standardisation foresight. Therefore, many policymakers and standards organisations call for more systematic and future-oriented analyses of standardisation, which: (i) closely examines structural characteristics of complex technological systems; (ii) integrates diverse aspects of innovation that impact standardisation, including research, market, and policy perspectives; (iii) allows coordinated engagement of various stakeholders involved in interdisciplinary domains; and (iv) captures how they all evolve over time with long-term perspectives.

Accordingly, a number of foresight exercises and initiatives have recently been conducted in various areas across the world, with standardisation roadmapping as one of the most adopted practices with the above characteristics. Due to its holistic and integrative perspectives with appropriate level of analysis, the roadmapping approach also appears to be a potentially useful tool for systematic and future-oriented analyses of standardisation (see section 4.1 for further discussion) in the context of innovation systems. Nevertheless, further research is needed to explore how such foresight exercises can be structured and managed, using a more practical and operational tool incorporating important strategic dimensions that need to be accounted for.

In order to fill these gaps in both theory and practice, the current research attempts to develop a systematic and comprehensive framework for exploring complex and dynamic interplays between standardisation and innovation with long-term perspectives. Building on the innovation systems functions approach, such framework can be developed by adopting the holistic approach of strategic roadmapping and integrating it with important dimensions of standardisation identified in existing literature. It should, however, be noted that the current research does not aim to develop an all-encompassing model explaining every possible interactions between them, but rather seeks to provide a flexible and adaptable framework highlighting key categories of their potential interplays from more systematic perspectives. A process model for using this conceptual framework as a strategic foresight tool is also required, to help standards organisations and policymakers in developing standardisation strategies in highly complex technological systems. The research will not only produce increased understanding of standardisation in broader systems of technological innovation, but also provide practitioners with new insights on how to manage standardisation effectively at a policy level to support overall innovation systems.

2.6 Concluding Remarks

Despite the increasing awareness of the importance of standardisation in technological innovation, existing literature are narrow and fragmented, focusing on only certain aspects of standardisation with limited perspectives. Focusing on main activities performed by various actors involved in overall innovation systems, the functions approach offers opportunities to systematically explore diverse roles of standardisation in innovation, but is too abstract. Existing frameworks representing various roles and functions of standardisation provide more detailed analyses, but are neither complete nor consistent. Therefore, a systematic, integrative, and comprehensive framework with more detailed level of analysis is needed to increase our understanding of how standardisation supports overall innovation systems. Needs for such frameworks are also identified among practitioners, to help standards organisations and policymakers in anticipating standardisation needs and developing relevant strategies, which are becoming increasingly important in complex systems of modern technologies. In order to address such gaps in both theory and practice, the current research attempts to build a roadmap-based framework and process model, for exploring complex and dynamic interplays between standardisation and technological innovation, and allowing strategic policy foresight to support timely and effective standardisation.

3. METHODOLOGICAL APPROACH

Based on the review of literature and practice, this chapter starts by refining the research question and objectives to address the research gap identified in the previous chapter. Then, it presents appropriate philosophical position, research strategy, research design, and research methods adopted to answer the research question, along with rationales for their choices. This chapter concludes with the assessment of these methodological approaches, evaluating the quality of research design and the stability of research outputs.

3.1 Research Objectives

The high-level question guiding this research is:

> *How might complex dynamic interplays between standardisation and technological innovation be analysed systematically, and subsequently accounted for in strategic policy foresight?*

The review of literature with regard to the above research question reveals that there are high levels of complexity and variations associated with standardisation in support of technological innovation, in terms of: elements of technological innovation, functions of standardisation, stakeholder types, and stages of technology lifecycles. There is, however, limited academic literature exploring these issues and their interdependencies from a holistic perspective. The review of practice further demonstrates that there are increasing challenges associated with future-oriented analyses of these dynamics in modern technologies, which are complex, interdisciplinary, and systems-like in nature. Objectives of this research are thus defined as follows:

- Identify the various elements and factors that characterise standardisation in the context of technological innovation with more detailed level of analyses.

- Develop a framework that captures these elements and factors, and test its potential to systematically explore complex and dynamic interplays between standardisation and technological innovation.
- Explore potential of the framework to be used by standards organisations and policymakers in strategic foresight for timely and effective standardisation.
- Develop a process model for using the framework for future-oriented analyses of standardisation, particularly in complex, multidisciplinary technological systems.
- Provide policy implications for using the framework and process model for systematic and strategic analyses of standardisation, particularly roles of government and other public agencies.

3.2 Philosophical Position

In order to select appropriate research approach, design, and methodology to achieve the above objectives, it is essential to adopt an underpinning philosophy of enquiry suitable for the current thesis. Positivism and social constructionism are two main philosophical positions or paradigms; their key differences are illustrated in Table 3.1.

Table 3.1 Comparison between research paradigms (Easterby-Smith et al. 2002; Creswell 2003)

	Question	**Positivism**	**Social constructionism**
Ontology	What is the nature of reality?	Reality is objective and singular, apart from the researcher	Reality is subjective and is inseparable from the researcher
Epistemology	What is the relationship of the researcher to that research?	The researcher is independent from what is being researched	The researcher interacts with what is being researched
Methodology	What is the way to approach problems and seek answers?	· Focus on facts · Deductive process / formulate hypotheses and test them · Cause and effect · Operationalising concepts to measure · Taking large samples	· Focus on meanings · Inductive process / develop theories through induction · Mutual simultaneous shaping of factors · Small samples investigated in depth

As this research aims to increase general understanding of complex phenomena of study – i.e., standardisation dynamics in the context of technological innovation – of which there are only limited theories, it is exploratory and theory-developing in nature, requiring the researcher's interactions and interpretations of the reality. The investigative approach with the underpinning philosophical stance of social constructionism is thus more suitable than positivism for the current study. This approach is also appropriate because of its suitability for analysing complex situations to identify and understand the variables and their interacting mechanisms (Creswell 2003).

3.3 Research Strategy

3.3.1 Flexible Design Strategy

Given the complex and exploratory nature of the research question, there is a need to first acquire deeper understanding of the phenomena of study, before building on it in subsequent research phases. According to Robson (2011), a flexible design strategy is highly appropriate for such studies, where the design evolves during data collection. As data are typically non-numerical, it is often referred to as a qualitative research strategy. Robson (2011) provides three main traditions in qualitative research, which are summarised in Table 3.2.

Table 3.2 Three traditions in qualitative research (Robson 2011)

	Main characteristics	Additional features
Case study	The focus is on one or more cases (e.g., individual person, group, setting, organisation, etc.), taking their contexts into account.	· Typically involves multiple methods of data collection. · Can include quantitative data, though qualitative data are almost invariably collected.
Ethnographic study	The focus is on the description and interpretation of the culture and social structure of a social group.	· Typically involves participant observation over an extended period of time. · Typically written in a narrative, literary style.
Grounded theory study	Main concern is to develop a theory of the particular social situation forming the basis of the study.	· Provides a systematic and coordinated strategy. · Particularly useful in applied areas of research, where theoretical approach is not clear.

3.3.2 Building Theory from Case Studies

Case studies are often preferred in areas of public policy, for an empirical investigation of a contemporary phenomenon within a real-life context (Yin 2009). By conducting in-depth studies of processes of innovation and relevant standardisation activities within a real-life context, case studies allow researchers to develop clearer and richer explanations about a subject that has not been well understood yet (Yin 2009). Exploratory case studies also have the following advantages:

- They rely on multiple sources of data, allowing the researcher to obtain extensive details about the case viewed from various perspectives (Yin 2009).
- They allow great flexibility in designing complex, open-ended research with a variety of methods, adding richness and comprehensiveness in exploring new concepts (Cooper & Schindler 2008).

This research particularly adopts the approach of building theories from multiple case studies, as is appropriate for research on a new topic or when taking a novel perspective on an already researched topic (Eisenhardt 1989). Eisenhardt (1989) also identifies the following strengths and benefits of using case studies in exploratory and theory-building research:

- They are likely to generate a novel theory, as creative insight often arises while researchers try to reconcile evidence across cases and types of data, leading to the creative reframing of a new theoretical vision.
- The emergent theory is more likely to be empirically valid, as the theory-building process is intimately tied with evidence.

However, there are also some weaknesses and limitations of the approach (Eisenhardt 1989):

- The intensive use of empirical evidence may result in theory which is overly complex.
- Narrow and idiosyncratic theory may be developed, making it difficult to raise the level of generality of the theory.

In order to overcome such limitations and challenges, a number of tactics suggested by Eisenhardt & Graebner (2007) is adopted to create thoughtful research design, including: thorough justification of theory-building, theoretical sampling of cases, interviews that limit informant bias, rich presentation of evidence in tables and appendixes, and clear statement of theoretical arguments. In addition, engagements with practitioners – i.e., verification interviews – that supplement the primary case study method have been adopted at a later stage of the research, for the purpose of triangulation, testing, and generalising results (see section 3.4 for details).

For a flexible design research like the current study, it is difficult to predetermine the number of cases or sources of evidences (e.g., documents or interviews) required, until the actual research is carried out. According to Strauss & Corbin (1990), the basic notion is to carry on until eventually reaching a point of saturation, where new cases add little or no new information. In general, between four and ten cases are agreed to be adequate by Eisenhardt (1989), whereas Robson (2011) suggests approximately 30 to 50 interviews. The number of cases selected and sources of evidences used for each case are discussed in main chapters of this thesis (i.e., Chapters 4, 5, and 6), along with rationales for their selections.

3.4 Research Design

In order to develop a framework and a process model for using it for systematic and future-oriented analyses of standardisation, research described in this thesis utilised the process of building theories from case studies introduced by Eisenhardt (1989) as the foundation of its research design. Highly iterative and tightly linked to data, the process involved recursive iteration between (and thus constant comparison of) the emergent theory with the evidence from case studies and existing literature (Eisenhardt 1989). This process was adjusted in the context of the research questions, and consisted of multiple research phases with data analysed during and after each case study (and each phase of research), leading to more refined framework and process model.

Figure 3.1 summarises the four main research phases: (i) literature review to develop the initial preliminary framework and process model, (ii) multiple case studies to further develop the framework and process model, (iii) single in-depth case study to refine the framework and process model, and (iv) interviews to verify the framework and process model. Circular arrows indicate constant iteration of development, testing, and refinement of the framework and process model at each phase of research.

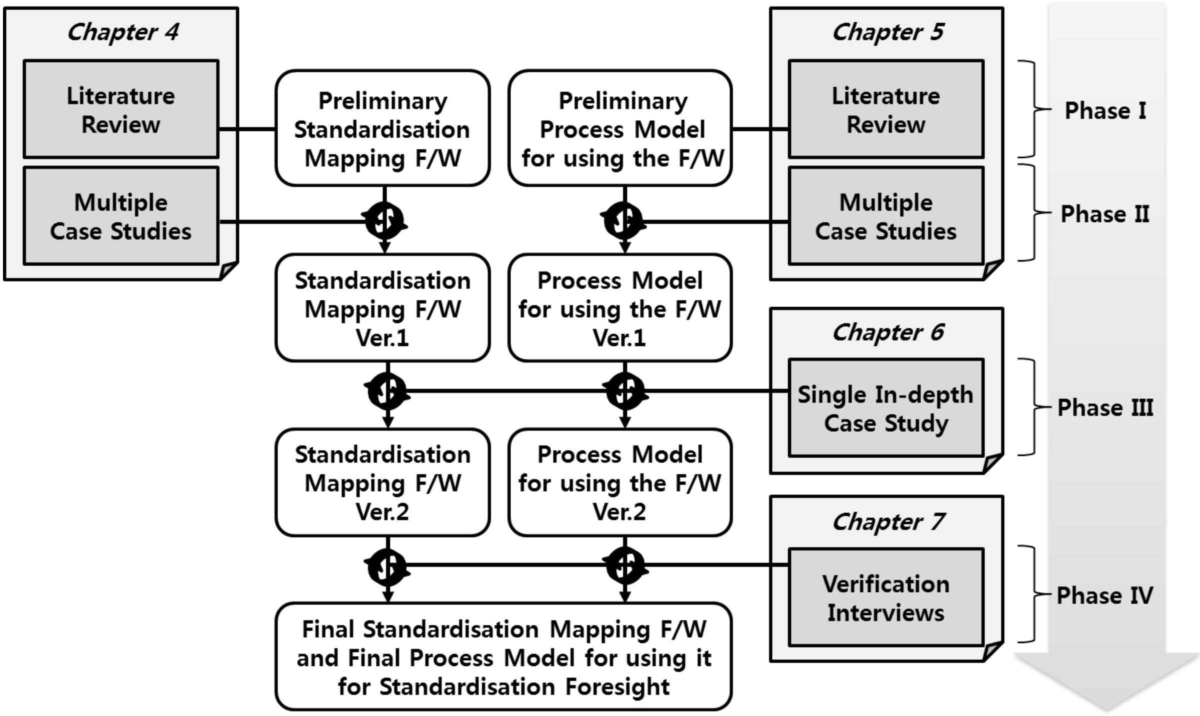


Figure 3.1 Overall design of the current research

Phase I: Literature Review

Due to the high level of complexity and variations associated with the phenomena being studied, extended reviews of literature were first carried out, exploring basic elements and factors that characterise standardisation in the context of technological innovation with detailed level of analyses. Existing conceptual models as well as other relevant literature with potential insights into these complex dynamics were reviewed, in order to identify a systematic and integrative list of important elements and features of standardisation. They were then used to build preliminary versions of the framework and process model, as building on established frameworks and process models from existing research is considered to be more effective than creating new constructs or building theories from scratch (Saunders et al. 2007). Eisenhardt (1989) also noted that *a priori* specification of constructs drawn from literature in related areas of the research context can help shape the initial design of theory-building research. Although this might be tentative, it may provide a firmer empirical grounding for the emergent theory, and permit the researcher to measure constructs more accurately as research progresses (Eisenhardt 1989).

Phase II: Multiple Case Studies

As there are only limited theories in existing academic literature, multiple case studies were carried out using the preliminary framework and process model as bases, in order to reveal additional features that are potentially relevant or useful for their further development. Due to limited time and resources available for this thesis, these were inevitably exploratory, seeking first order elements for the development of framework and process model and providing initial tests for their feasibility. Three cases were studied for the development of standardisation mapping framework (ver.1); whereas six cases were studied for the development of process model for using the framework (ver.1), through two rounds of iteration for increased validity. Rationales for and details of these case studies are further discussed in sections 4.3.1 and 5.2.1, respectively. Data collected mainly from documents and expert interviews were analysed through within-case analyses and cross-case comparisons, leading to the development of more robust framework and process model that are applicable in a variety of different contexts. The findings of case studies also identified specific areas and issues that require further exploration in the next phase.

Phase III: Single In-depth Case Study

A single in-depth, longitudinal case study was carried out, to test and refine the proposed framework and process model by providing deeper understanding of a number of issues and factors where further investigation was needed. The historical case study of PV technology was selected because of the high level of complexities associated with it, adding intricacy and variety to the study (see section 6.1.1 for details). Drawing on a large number of documents and expert interviews, the case study suggested the value of features embedded in the framework and process model. It also provided additional insights to further develop and improve them – though marginally – by exploring complex and dynamic interplays between standardisation and innovation in greater detail. The standardisation mapping framework developed in phase II was used for data collection and analyses of this in-depth case study; detailed methods used for the study are further discussed in section 3.5.

Phase IV: Verification Interviews

Lastly, a series of expert interviews were carried out to verify completeness and general practicality of the proposed framework and process model. Supplementing previously conducted case studies, they were designed to overcome potential weaknesses of case studies in theory-building research, such as generation of overly complex theories (as discussed in section 3.3.2). Performed in two rounds of iteration for increased validity, verification interviews led to the clarification of the framework and process model, and provided practical implications and guidance of operationalising them for standardisation foresight. Selection of participants and interview details are further discussed in section 7.1.

3.5 Research Methods

3.5.1 Data Collection Methods

Various sources of data can be used for case studies, and Table 3.3 summarises characteristics and examples of those relevant to this research. A variety of sources can not only increase the richness of data, but also ensure that different data complement each other, improving validity of the research. Documentation and interviews were extensively used as key sources of evidence.

In particular, semi-structured interviews, combining structure and flexibility (Robson 2011), were used throughout the research. Interview protocols guiding the conversation with interviewees were developed before collecting data at each phase, in order to increase the reliability of the research (see Appendix B for an example of interview protocols). The protocol helps the researcher to focus on the subject of the case study, and also anticipate problems that may arise during further research (Yin 2009). Face-to-face interviews were performed wherever possible, but nineteen out of ninety-one interviews (for case studies and verification interviews) had to be conducted via phone or e-mails. Most interviews lasted approximately forty-five minutes to an hour. They were recorded when permissions were obtained, and subsequently transcribed for analysing natural language data.

Table 3.3 Sources of evidence for case studies (based on Yin 2009)

	Strengths	Weaknesses	Examples relevant to this research
Documentation	· Stable – can be reviewed repeatedly. · Unobtrusive – not created as a result of the study. · Exact – contains exact names, references, and details of an event. · Broad coverage – long span of time, many events, and many settings.	· Retrievability – can be difficult to find. · Biased selectivity, if collection is incomplete. · Reporting bias – reflects (unknown) bias of author. · Access – may be deliberately withheld.	· Published standards · Official policy-related documents published by government and other public agencies · Official technical reports published by research laboratories · Industry trade magazines · Journal papers
Archival records	· *[Same as those for documentation]* · Precise and usually quantitative.	· *[Same as those for documentation]* · Accessibility due to privacy reasons.	· Records of technical workshops / meetings
Interviews	· Targeted – focuses directly on study topics. · Insightful – provides perceived causal inferences and explanations.	· Bias due to poorly articulated questions. · Response bias. · Inaccuracies due to poor recall. · Reflexivity – interviewee gives what interviewer wants to hear.	· Interviews with policymakers, academics, and participants in standardisation (adopting visual mapping process for the PV case study)
Direct observations	· Reality – covers events in real time. · Contextual – covers context of 'case'.	· Time-consuming and costly. · Selectivity – broad coverage difficult without a team of observers. · Reflexivity – event may proceed differently because it is being observed.	· Observation of technical meetings of formal SDOs

For the in-depth case study of PV technology during the third phase of the research, interviews partially adopted the *Expert Scan* method developed by researchers at Centre for Technology Management, University of Cambridge (Ford et al. 2011). As an interview-based visual mapping process, the approach enabled to capture hidden insights from interviewees' past experiences and personal perspectives on the evolution and development of complex systems. Given significant advantages of the visual interview method and its compatibility with the roadmap-based framework proposed in this research, this method was an effective way to record historical interview-based accounts of dynamics between standardisation and development of PV technology. Yet, the mapping technique was used as a supplementary method to support data collection during expert interviews, rather than solely adopted as the main method of data collection.

This was because of not only its low level of maturity as an established research method, but also some practical issues associated with this research; producing a detailed map covering the entire history of PV standardisation over the past forty years was almost impossible for individual interviewees, due to their inability to recollect a long-term history, as well as their expertise in specific areas only. Hence, a pre-populated map generated from secondary sources (similar to Figure 6.1) was shown during interviews, where interviewees presented their opinions and perspectives on activities and their dynamics shown on the map. It was a useful supplementary tool to not only stimulate interviewees' narratives on past experiences, but also help draw their thoughts on standardisation within a broader context of innovation systems.

3.5.2 Data Analyses Methods

Three main methods of data analyses were adopted in this research: within-case analyses, cross-case comparisons, and narrative analyses. In particular, within-case analyses and cross-case comparisons have been extensively used for analysing multiple case studies during the second phase of the research. Often used for building theory from case studies, within-case analyses helped investigators with the generation of insights while dealing with deluge of data, thus allowing unique patterns of each case to emerge and giving the researcher a rich familiarity with each case which, in turn, accelerated cross-case comparisons (Eisenhardt 1989). Coupled with within-case analyses, cross-case comparisons searched for patterns across different cases, through the use of structured and diverse lenses on data (Eisenhardt 1989). A number of tactics introduced by Eisenhardt (1989) have also been used to enhance the probability of developing accurate and reliable theories with a close fit with the data, including: looking for similarities within the same categories or dimensions, listing the similarities and differences between pairs of cases, and dividing the data by data source.

In addition, narrative analyses were used for the in-depth case study during the third phase of this research, to analyse data that are mainly composed of texts from documents and interview transcriptions. Employing elements of storytelling to build the story, it was used to describe the sequence of events in a case study based on temporal ordering of events and key actors (Easterby-Smith et al. 2002). Prose descriptions of key events and activities were ordered into a sequential order, and explored for evidence of how complex and dynamic interplays between standardisation and innovation evolved over time; they were then visually organised and structured using dimensions of the standardisation mapping framework (see Figure 6.1). The narrative and visualisation were later presented to four interviewees – i.e., experts with greatest experience spanning the history of PV standardisation (see section 3.6.2 for details) – for validation, allowing the researcher to amend any possible misinterpretations of their recollections or identify additional patterns.

3.6 Assessment of Methodological Approach

3.6.1 Quality of Research Design

The quality of research outputs depends, of course, on the quality of the research design. Yin (2009) identifies four tests that are commonly used to establish the quality of empirical social research, along with associated tactics to be used, particularly with case studies. Table 3.4 summarises these tests and how they have been dealt with in the current research, to ensure that relevant criteria are addressed, increasing quality and robustness of the research design.

Table 3.4 Four tests to establish the quality of case study research (based on Yin 2009)

Tests	Explanations	Tactics adopted in this research
Construct validity	Identifying correct operational measures for the concepts being studied	· Use of multiple sources of evidence · Establishing a chain of evidence · Having key interviewees review draft case study report / narrative
Internal validity	(For explanatory or causal studies only) seeking to establish a causal relationship, whereby certain conditions are believed to lead to other conditions, as distinguished from spurious relationships.	· Not applicable for this research, which is descriptive and exploratory in nature
External validity	Defining the domain to which a study's findings can be generalised.	· Use of replication logic in multiple case studies
Reliability	Demonstrating that the operations of a study – such as data collection procedures – can be repeated, with the same results.	· Use of case study protocol · Developing case study database

Despite such measures, case studies are often criticised for the lack of external validity, i.e., the level of generality of the theory cannot be raised from substantive to formal. However, the current research does not aim to develop an all-encompassing model explaining every possible interactions and interdependencies between standardisation and innovation in any contexts. It rather seeks to provide a flexible and adaptable framework with more systematic perspectives, highlighting key categories of their potential interplays by drawing attention to important dimensions of standardisation in the context of innovation. Cases have been selected deliberately to demonstrate its usability and value in revealing these dynamics that would not otherwise be seen; rationales for their selections are further discussed in sections 4.3.1, 5.2.1, and 6.1.

Limited numbers of cases (due to time and resource constraints) may also risk offering a poor basis for generalisation. However, this has been addressed by a large number of data collected throughout this research, particularly secondary documents published by government and other public agencies with refined and saturated information. A large number of interviews (forty-two) for the in-depth case study in phase III also complement the need for a richness of data to develop a deeper understanding of complex and dynamic interplays between standardisation and innovation. The issue of theoretical stability and saturation is further discussed in the next section.

3.6.2 Stability of Research Outputs

In order to ensure that sufficient amount of data have been gathered for each study (both case studies and verification interviews) throughout this research, interviews have been conducted until a point of saturation – i.e., where no new insights were gathered – was reached. Figure 3.2 shows an exemplar curve showing theoretical saturations observed from the single, in-depth case study on standardisation of PV technology. According to the trend line, new ideas gathered from interviewees increased in the beginning, not only because changes to interview protocols were made after the first six preliminary interviews, but also as the researcher's knowledge of the phenomena increased at this stage. Gradual saturation of new distinct ideas from data suggests that most of insights into the phenomena have been identified. It should also be noted that interviewees 7, 13, 17, and 27 provided particularly large number of ideas, since they had considerably long experience on broad areas of PV standardisation.

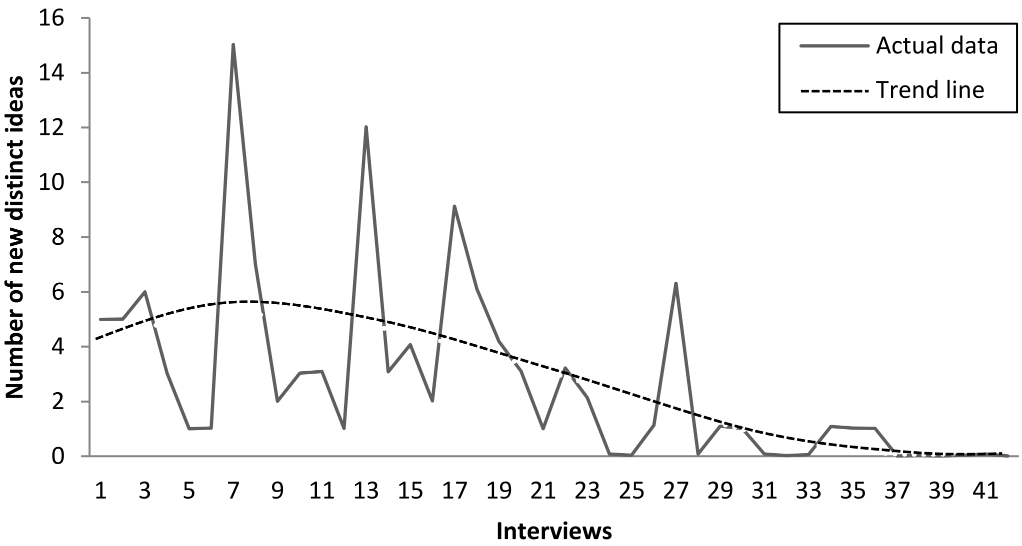


Figure 3.2 Number of new distinct ideas identified from interviews of the in-depth case study

Such theoretical saturation has also been reached with the development of framework and process model; Figure 3.3 plots the number of new features incorporated in the framework and process model after each study, along with trend lines. Limited new knowledge has been gathered from later case studies, as the researcher has been observing phenomena already seen from previous case studies. No further case studies have thus been conducted, as significant stability of the framework and process model has been demonstrated.

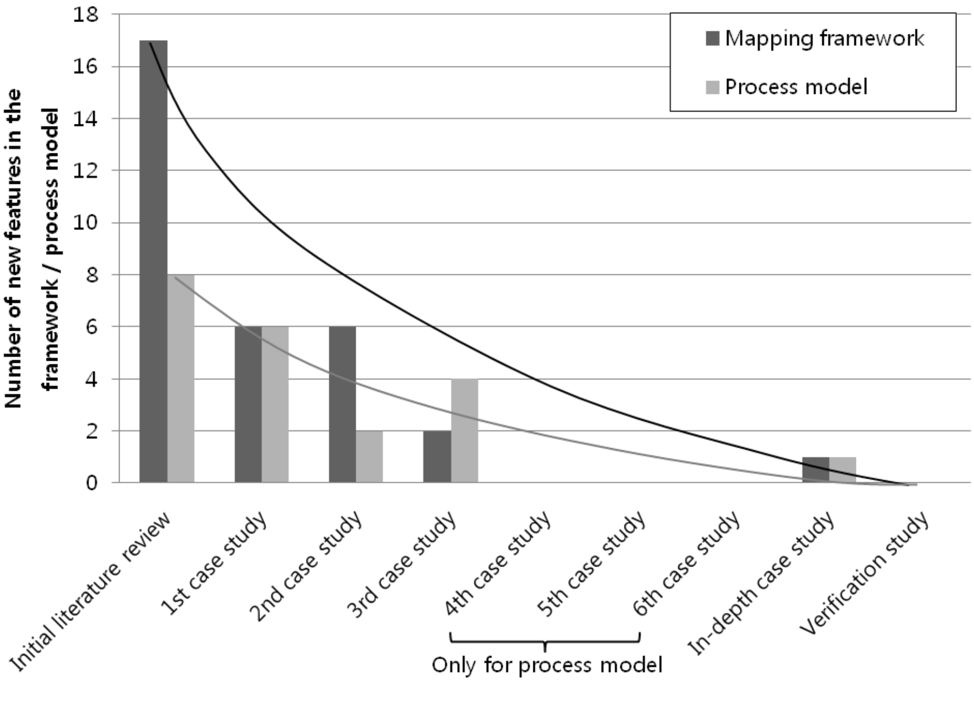


Figure 3.3 Number of new features introduced in the framework and process model

3.7 Concluding Remarks

In order to address the research gap identified in the previous chapter, social constructionism is considered to be a more appropriate philosophical approach for the current study with exploratory and theory-developing characteristics. It adopts a flexible design approach of building theories from multiple case studies, which allows using a combination of different methods for data collection and analyses to build theories that are closely linked to data. A stage-based research comprising four phases – i.e., literature review, multiple exploratory case studies, single in-depth case study, and verification interviews – is designed, utilising various methods – such as within-case analyses, cross-case comparisons, and narrative analyses – to analyse data collected mainly from documentations and expert interviews. Compatible with the proposed roadmap-based framework, visual mapping technique is considered to be particularly effective for collecting useful insights from interviewees and analysing their narratives systematically. A variety of tactics and measures have been also adopted to ensure the quality of research design and the stability of research outputs. Details of data collection and analytical processes at each phase of the research are further discussed in following chapters.

4. DEVELOPMENT OF FRAMEWORK

This chapter* presents a roadmap-based framework developed for systematic analyses and foresight for standardisation in support of innovation. First, theoretical perspectives and approaches relevant to general strategic roadmapping are discussed, exploring its potential to map the evolution of complex and dynamic interplays between standardisation and innovation. Conceptual foundations relevant to standardisation in the context of technological innovation are then highlighted, leading to the development of a preliminary framework for standardisation mapping. It is followed by discussions of case studies in a number of technological sectors, testing the basic utility and demonstrating the potential of the preliminary framework. They not only illustrate a range of phenomena and patterns associated with complex dynamics of standardisation in the context of technological innovation, but also provide additional insights for further development of the preliminary framework. Based on these findings as well as additional literature review, a more developed framework for standardisation mapping is presented.

4.1 Introduction to General Strategic Roadmap

The review of literature in Chapter 2 highlights the need for a holistic and integrated framework capturing various aspects of standardisation with a greater level of detail, to increase our understanding of its complex and dynamic interactions with innovation, and to support relevant foresight analyses. Building on established frameworks is considered to be more effective than creating new constructs from scratch (see section 3.4), and the review of practice suggests that the roadmapping approach has significant potential for such systematic

* Part of the research contained within this chapter has been published as C. Featherston, J. Y. Ho, L. Brévignon-Dodin, and E. O'Sullivan (2016) Mediating and catalysing innovation: A framework for anticipating the standardisation needs of emerging technologies. *Technovation*, 48-49, pp. 25-40.

and future-oriented analyses of standardisation. In order to investigate the utility and practicality of the approach for the current study, it is first appropriate to explore general strategic roadmapping in more detail.

4.1.1 Strategic Roadmap Framework

Widely adopted by many organisations in different sectors and at various levels, strategic roadmapping is recognised as a powerful technique for supporting technology foresight and innovation planning (Phaal et al. 2010). This is due to the fact that a roadmap provides a coherent, holistic, and high level integrated view of complex systems, while displaying the interactions between technologies and other social mechanisms over time (Kostoff & Schaller 2001; Groenveld 2007; Popper 2008). It does so by drawing key themes and perspectives of the system – including scientific, technological, and market development – together in a layered form.

A roadmap can take a variety of forms, but the generic strategic roadmap is a time-based chart, comprising various layers such as commercial, regulatory, systems, and technological perspectives (Kostoff & Schaller 2001; Groenveld 2007; Popper 2008). Figure 4.1 shows the roadmap framework developed by Phaal & Muller (2009), incorporating three main elements of a strategic roadmap: (i) time scale on horizontal axis; (ii) key themes and perspectives representing innovation systems on vertical axis; and (iii) significant events and milestones showing the progression of technological innovation. Composed of various aspects and factors that are considered to play important roles in innovation systems, key perspectives and viewpoints of each layer fall into one of three broad categories as follows:

1) Commercial and strategic perspectives: the market demand dynamics where opportunities for creating and capturing value occur, including considerations of broad market trends and drivers, customer needs, and specific industrial dynamics.
2) Design, development, and production perspectives: the mechanisms and processes used to appropriate value through delivering products and services, including considerations of business models and strategies, applications, and sales.
3) Technology and research perspectives: the capability supply dynamics used to generate products and services, including considerations of R&D, finances, human resources, and management systems. (Phaal & Muller 2009, p.40)

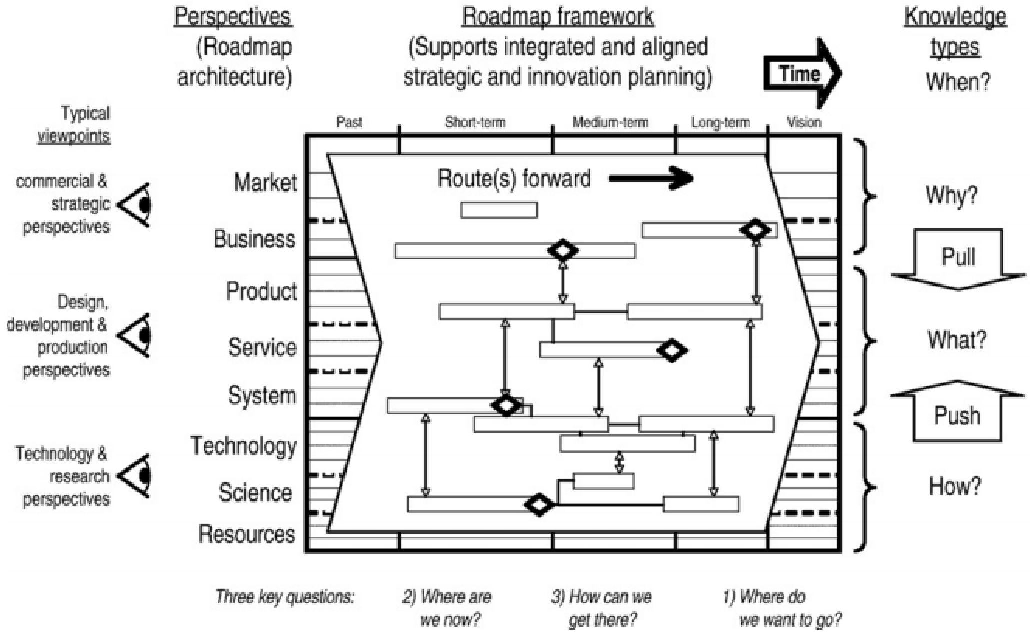


Figure 4.1 Architectural framework of strategic roadmapp (Phaal & Muller 2009, p.40)

4.1.2 Characteristics and Uses of Roadmap Framework

The 'systems' viewpoint with a detailed level of analyses is a key benefit of strategic roadmap framework in complex and profound innovation problems. Providing a concise and high level integrated view of the multidisciplinary cross-functional working system, it helps cope with dynamic and complex environments, by decreasing the level of complexity and overcoming the restricted capability of human to process information (Saritas & Oner 2004; Amer & Daim 2010). The framework is not too abstract either, as it effectively captures what is happening in a system, by organising and presenting critical information in a disaggregated manner. Due to its flexibility and adaptability in addressing many strategic issues at different levels of granularity, strategic roadmapping has been adopted by many private and public organisations to understand, plan, and promote innovation activities (Phaal & Muller 2009).

A large number of public-domain roadmaps have been produced over the past decade, many of which are 'supra-company' roadmaps, developed by collaborations between more than one organisation (de Laat & Mckibbin 2003). Usually sponsored or stimulated by a trade association, government department, or other interested groups, this type of roadmap is developed by a team of experts from various organisations and disciplines to influence policy, research funding, and standards (Phaal et al. 2009). Collecting, organising, and presenting the critical information needed for understanding complex systems, roadmapping activities provide the appropriate context of the gaps, by identifying useful information, such as barriers, drivers, goals, planned activities, and priorities, all with reference to timeframes (Garcia & Bray 1997; Kostoff & Schaller 2001; Phaal et al. 2010). Thus helping identify key gaps in achieving technological innovation and development, roadmaps guide multiple organisations to collaboratively develop appropriate strategic plans to achieve their visions and goals, with the associated communication benefits as well.

4.1.3 Roadmap-based Framework for Systematic and Future-Oriented Analyses

Because of its structure and associated characteristics, the generic roadmap framework is able to provide a holistic and systematic view of complex and dynamic systems of standardisation in technological innovation, enabling their evolutions "to be explored and mapped, supporting innovation and strategy development (Phaal et al. 2009, p.287)." In particular, layers of the roadmap can be configured to correspond to detailed categories of technology and innovation elements, which are used to explore key standardisation and other innovation activities, as well as dynamic interplays between them (Phaal & Muller 2009; Phaal et al. 2010). In addition, the framework offers the context to identify gaps where standardisation may be used to support innovation activities, and explore relevant considerations for strategy development. Hence, there is potential value of using the roadmap-based framework as a systematic, practical tool for analysing complex dynamics between standardisation and innovation, and developing relevant strategies for timely and effective standardisation.

By bringing consensus and creating a common vision among various stakeholders involved (Groenveld 2007; Popper 2008; Amer & Daim 2010), the roadmapping approach may also be useful for coordinated engagements required in strategic management and foresight of standardisation. Standardisation is intrinsically consensus-building activities of various parties involved (see section 2.1.3), and such coordination is becoming more significant, as technologies are becoming more complex and systematic, involving a vast range of stakeholders from different backgrounds and domains (see section 2.4.3). The roadmap-based framework may be used to effectively address challenges associated with the engagement of these various stakeholders, as using the roadmap framework improves cross-functional communication and coordination for innovation systems (Garcia & Bray 1997; Amer & Daim 2010).

4.2 Preliminary Framework for Standardisation Mapping

For valid and appropriate use of the framework for analysing and managing standardisation in support of innovation, various issues relevant to standardisation identified in existing literature need to be integrated to the generic roadmap framework (shown in Figure 4.1). Providing useful insights and conceptual foundations, they can be readily introduced to the framework which is flexible and adaptable in nature. This section discusses how the roadmap framework was adapted to develop an initial preliminary framework for systematic and future-oriented analyses of standardisation, through an extended literature review.

4.2.1 Dimensions of Standardisation

Existing frameworks for standardisation and innovation (discussed in section 2.3) identify three important factors to be considered in analysing complex and dynamic interplays between them: technology and other innovation elements associated with standardisation, types and functions of standards, and how they evolve over time. Each representing '*what*', '*why*', and '*when*' aspect of standardisation, respectively, these are important '*dimensions*' of standardisation to be incorporated into the framework for analysing how it supports technological innovation. Each dimension is explained in more detail as follows.

4.2.1.1 '*What*' innovation activities are relevant to standardisation – categories of technology and other innovation elements

In order to better understand complex and dynamic interplays between standardisation and innovation, particularly in modern technologies, it is important to first understand complex systems of technological innovation and their elements in greater detail. Existing standardisation frameworks, particularly the one by Tassey (2000, 2015), suggest that standards have different strategic and marketplace roles depending on categories of technology and other innovation elements involved, hence different rationales for and the processes by which standards are set. When exploring standards-related issues of general innovation strategies, innovation actors and other stakeholders are also concerned the most about their innovation activities that are relevant to, and influenced by, particular standardisation efforts. Therefore, it is important to first distinguish different categories of technology and other innovation elements relevant to standardisation, before discussing their roles and functions.

Adopting three broad thematic categories of elements for technological innovation suggested by strategic management and foresight literature (e.g., Groenveld 2007) – i.e., technology, product, and market –, standardisation relevant to each element may be categorised into technology-supporting, production-facilitating, and market-enabling, respectively. These are further refined using various perspectives of roadmap architecture introduced by Phaal & Muller (2009), as well as detailed categories of technologies suggested by Tassey (2000). As the current research focuses on standardisation challenges in complex technological systems, particular attention is paid to technology-related elements of innovation systems, whereas some non-technological elements – such as resources and services – are either eliminated or integrated in other related categories. While customisable to accommodate particular characteristics of technical domains under consideration, the following is the general list of sub-categories for '*what'* technology and innovation elements are relevant to standardisation.

- *Science base*: Basic standards related to basic scientific principles – either method, procedural, or normative (e.g., frequency standards) – represent the most accurate statements of the fundamental laws of physics, qualifying as pure public goods (Tassey 2000). Unit and reference standards that define basic physical properties, e.g., units of mass, length, and time, are also important basic metrology (Krechmer 2000).
- *Infratechnology*: As technology whose development is driven by other systems or applications (Muller 2016), infratechnology provides varied and critical technical infrastructure support for the development of generic technology; e.g. applied or industrial metrology (such as measurement and test methods), interface standards, scientific and engineering databases, and standard reference materials (Tassey 2000). As such standards have large public good contents which are critical to the entire industry's efficiency, both industry and government investments are required (Tassey 1986).
- *Generic / platform technology*: As fundamental technical concepts derived from basic science which are critical for specific product innovations, generic or platform technology is configured and reconfigured by industry to create proprietary technologies (Tassey 2000; Keenan 2003).

- *Proprietary technology*: It is core technology where the company is adding value (Muller 2016) by formulating the concept from generic technology into prototype products with specific performance specifications (Tassey 1986; Blind & Gauch 2009). Typically involving one of the key attributes of a product, as opposed to the entire product, standards related to proprietary technologies convey direct competitive advantage to companies developing those technologies (Tassey 2000).
- *Product*: As actual market applications derived from generic technology, products are created in a form which can be produced in quantity at a cost to achieve market penetration (Tassey 1986). Product-related standards provide information to ensure that a product is adequate for a particular task, by specifying characteristics of the entire product (OTA 1992; CIE 2006).
- *Production*: Standards such as quality control or operational procedures specify the way in which a particular procedure or process is executed for efficient production (OTA 1992; Mansell 1995; Tassey 2000).
- *System*: As modern technologies are increasingly complex and integrated, system designs of how various components and products are interconnected to each other, and how they interact with complementing systems, need to be defined (Tassey 2015; Muller 2016).
- *Business / service*: Firms use standardisation to gain market power – often through dominant designs – through their business models or services (Betancourt & Walsh 1995; Grindley 1995).
- *Market*: Standardisation affect commercialisation and market development, by reducing uncertainties and transaction costs (David 1987).

4.2.1.2 '*Why*' standardisation is needed – roles and functions by various types of standards

All existing frameworks discussed previously (Tassey 2000; Sherif 2001; Blind & Gauch 2009) emphasise that there are different types of standards with different roles and functions, supporting different categories of technology and innovation elements to achieve their efficient development and utilisation. Many other academic and practice literature have also identified various types of standardisation, according to their purposes, functionalities, or economic problems they solve (e.g., OCST 1993; Sivan 1999; Blind 2004). Summarising these literature, the following list categorises five different types of standards with various roles and functions that are commonly used in technology.

- *Terminology / semantic standards* facilitate efficient communication among various stakeholders by defining key concepts and common language used to describe the system under consideration (OCST 1993; Blind & Gauch 2009; BERR 2008). They include unit standards defining physical properties, as well as classification and labelling schemes providing structured descriptions of entities (David 1987; de Vries 1999; Krechmer 2000).
- *Measurement / characterisation standards* provide scientific and engineering information for describing, quantifying, and evaluating certain attributes, characteristics, and functions of materials, parts, and products (Tassey 2000; Blind 2004; CIE 2006; Hatto 2013). Existing in the form of publications, electronic databases, or test methods, they increase research efficiency through more accurate research inputs and verifiable results, leading to higher productivity and quality through better process control (Tassey 2015).
- *Quality / reliability standards* specify acceptable performance criteria along various dimensions, such as functional levels, reliability, durability, efficiency, health and safety, and environmental impact (OCST 1993; BERR 2008; Tassey 2000). They can provide the point of departure for competition in an industry, and expand market share through performance assurance and reduction in transaction costs (Tassey 2000; Blind 2004; Tassey 2015).
- *Compatibility / interface standards* specify properties that a technology must have in order to be compatible (physically or functionally) with other products, processes, or systems (Blind & Gauch 2009; BERR 2008). They enable more competition by facilitating open systems, and help expand market opportunities by fostering network externalities (Blind 2004; Tassey 2015). Blind (2004) notes that there are two different types of network externalities: (i) direct externalities, where the utility function of an individual consists of a component independent from the network and a component depending on the size of the network, e.g., telephone network; and (ii) indirect externalities, generated in a paradigm in which each user must possess two or more components to derive benefits from the system, e.g., hardware and software. On the other hand, Gabel (1991) identifies two different types of compatibility: (i) multi-vendor compatibility between different producers' models of a product, and (ii) multi-vintage compatibility (or also called intergenerational compatibility by Foray (1998)) between successive generations of a product or a common set of complements.

- *Variety-reduction standards* are designed to limit a certain range or number of characteristics, including both physical dimensions (such as size) and nonphysical, functional attributes (such as data formats) (Tassey 2000; Swann 2010; Hatto 2013). Also called as similarity or simplification standards (OCST 1993; Krechmer 2000; Sherif 2001), they facilitate market formation and development in two ways: economies of scale by reducing the number of variations, and reducing suppliers' risks by shaping future technological trajectories (Blind 2004).

4.2.1.3 '*When*' to be standardised – real-time and timing relative to lifecycle

The issue of 'when' to be standardised is noted by many academic scholars and practitioners as an important factor, as standards can either foster or inhibit innovation largely depending on the timing of their development and implementation (see section 2.4.2). In addition to real-time, Sherif (2001) and Blind & Gauch (2009) highlight that various types of standards play different roles and functions at different stages, in terms of timing relative to technology lifecycles and innovation processes, respectively. In particular, Sherif (2001) discusses how standards can be anticipatory, participatory, or responsive, depending on when in the technology lifecycle they appear:

- *Anticipatory / prospective standards* are specified shortly after the introduction of technology, defining new concepts, features, components, and tools needed to proceed with trial implementations; they are thus essential for widespread acceptance of a device or service (Baskin et al. 1998; de Vries 1999; Sherif 2001). Particularly crucial for the interoperability of communication systems, many anticipatory standards can be found in ICT, including the Wireless Access Protocol (Egyedi & Sherif 2010). As there is a danger of including irrelevant details leading to complex and expensive implementations (due to lack of experiences and unclear market requirements), anticipatory standards should have well-defined scope and objectives, offering a minimum set of features and involving all interested parties (Sherif 2001; Egyedi & Sherif 2010).
- *Participatory standards* proceed in parallel with market growth and enhancements to the technology for refinements (de Vries 1999; Egyedi & Sherif 2010). Also called concurrent or enabling standards, they reduce production costs and spur incremental innovation (Egyedi & Sherif 2010). For example, the development of G.728 CCITT/ITU-T speech coding algorithm led to a major breakthrough in voice coding (Sherif 2001).

- *Responsive standards* arise late in the technology lifecycle, in order to improve efficiencies or reduce market uncertainties by creating network externalities (Egyedi & Sherif 2010). Although they offer a systematic way to distil available scientific information into useful technical constructs, there is a danger that incompatible approaches may become well entrenched when standards emerge too late (Sherif 2001).

4.2.2 Development of Preliminary Framework (Ver.0)

In order to develop an initial preliminary framework, the strategic roadmap framework by Phaal & Muller (2009) (Figure 4.1) is used as an underpinning framework, and modified to incorporate three important dimensions of standardisation identified in the previous section (see Figure 4.2). Firstly, the vertical axis of the framework is composed of a set of key activities that characterise innovation systems, representing '*what*' innovation activities interact with, or are influenced by, standardisation. Structured in a layered form, it is modified to capture more precisely detailed categories of technology and innovation elements relevant to standardisation. On the other hand, the horizontal axis of the framework represents time with extended long-term perspectives, capturing the issue of '*when*' to be standardised in terms of real-time. In addition to its timing relative to other innovation activities, the timing relative to technology lifecycles (i.e., whether standards are anticipatory, participatory, or responsive) may also provide additional useful information for systematic analyses. The framework thus provides a canvas where key innovation activities and other significant events can be recorded in boxes and mapped against the two axes, with linking lines indicating relationships and interdependences between them.

The most significant adjustment to the underpinning framework is the representation of standardisation activities. Standards or standardisation activities have been typically treated as a single category of innovation enabler (if considered at all), thus represented in a single layer of the roadmap framework (Phaal & Muller 2009; Phaal et al. 2010), as in the case of TSB (2012). However, as discussed in the literature review in Chapter 2, different types of standards with different roles and functions interact with different categories of technology and innovation elements, transferring different types of knowledge between them. In order to adequately reflect such mediating roles of standardisation in supporting various innovation activities and functions, it is more appropriate to represent them as linking lines. Hence, for any linkages where standardisation helps mediate between key activities and events, a circle with arrows are to be placed, describing interactions between standardisation and innovation. Letters in the circle indicate a diversity of roles and functions standards play in innovation, capturing the issue of '*why*' standards are needed.

Incorporating all three important dimensions of standardisation identified from the review of literature, the preliminary framework provides a holistic and integrative view on overall dynamics between standardisation and other innovation activities with extended long-term perspectives. With detailed characterisation and articulation of various dimensions of standardisation and relevant innovation activities, the framework allows observing and analysing these complex dynamics in a more comprehensive way, yet without losing details and clarity. It can also support standardisation foresight, by providing contexts for identifying gaps in linkages where standardisation is needed to facilitate knowledge diffusion, and highlighting any potential coordination, alignment, and sequencing issues related to standardisation activities. In order to verify and further develop this framework, the following section presents case studies, demonstrating how it can support such systematic and future-oriented analyses of standardisation in the context of technological innovation.

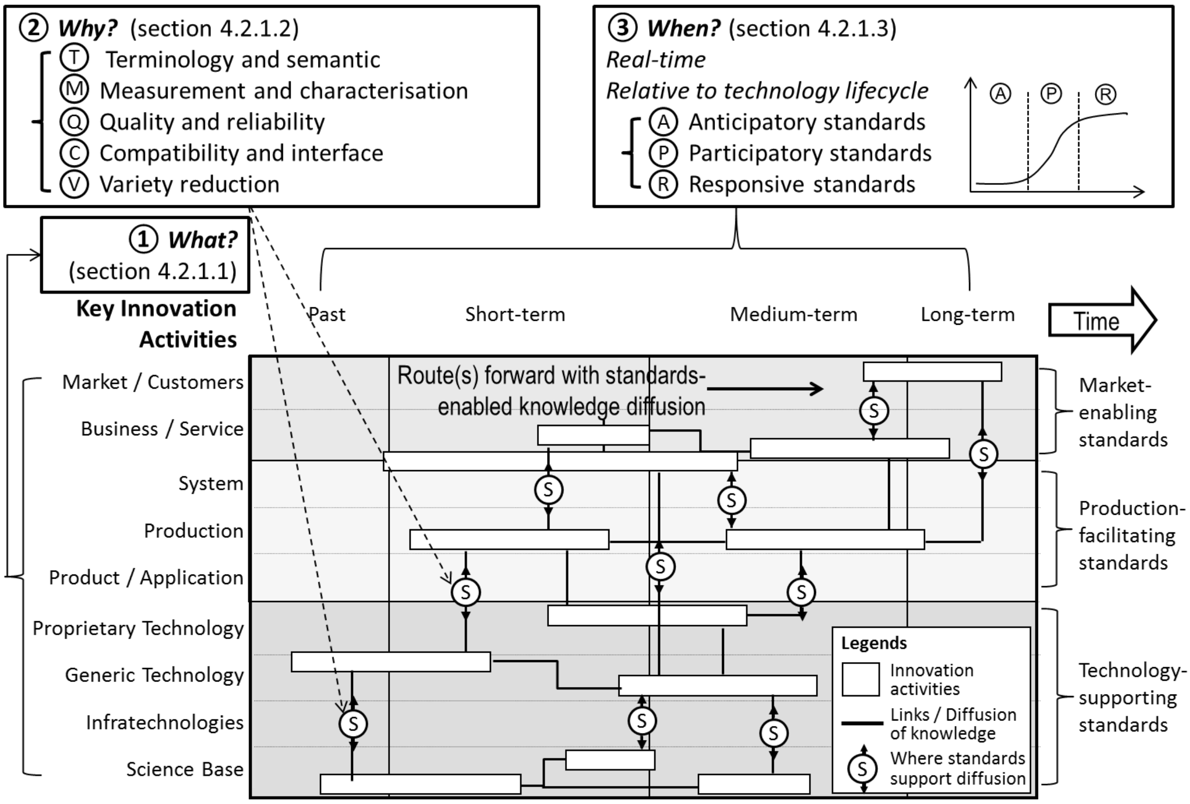


Figure 4.2 Preliminary framework for standardisation mapping (ver.0)

4.3 Case Studies for Testing and Developing the Preliminary Framework

Case studies are performed, to test basic utility and demonstrate underlying principles of the preliminary framework for standardisation mapping. Illustrating a range of patterns and phenomena associated with dynamics between standardisation and innovation, they also provide additional insights to improve and further develop the framework, all of which are discussed in this section.

4.3.1 Overview of Case Studies

The preliminary framework has been used in three emerging technology sectors where standardisation plays important roles: synthetic biology, additive manufacturing, and smart grid. They have different focus and scope in terms of categories of technology, and are at different stages of technology maturity. Each case thus has fundamentally different structure and nature of technological and innovation systems, resulting in different interests and characteristics of standardisation (see Table 4.1). Hence, each case study is expected to highlight different aspects and features of the preliminary framework, with particular focus on different sections of vertical and horizontal axes of the framework (see Figure 4.3).

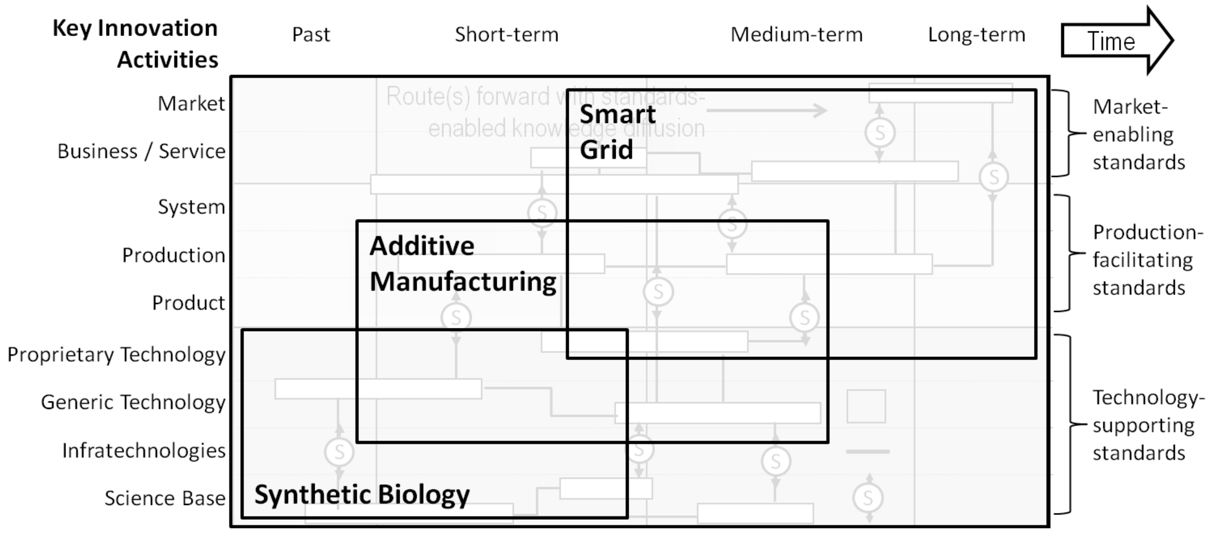


Figure 4.3 Various scope and focus of case studies

Table 4.1 Definitions and characteristics of three technology domains used in case studies

	Case 1: Synthetic Biology	Case 2: Additive Manufacturing	Case 3: Smart Grid
Definition	The redesign and engineering of biological systems and processes for new uses (Willetts 2013)	The fusion, sintering, or polymerisation of a material in layers as part of a fabrication process (Bourell et al. 2009)	Advanced power grid integrating many varieties of ICT with existing grid (NIST 2010)
Main type of technology	Generic technology	Production technology	System of technologies
Stage of technology maturity	Basic science converted to new engineering discipline	Engineering applications informed by new scientific discovery	Existing system with new technologies and sub-systems integrated
Standardisation interests	Definition and characterisation of parts, data sharing, and measurement	Printing resolution, characterisation and testing of varieties of processes and equipments	Interoperability and interconnection between devices and sub-systems
Number of data sources	25 documents, 1 expert interview	67 documents	44 documents

Mostly qualitative data were collected through the desk research of documentations, such as official reports and standards publications (see Table 4.1 for the number of data sources used in each case study). For each case, existing standards relevant to the technology were investigated to illustrate the type of information standards codify, what functions they perform in supporting innovation activities, and how they evolve across different stages of the innovation journey. As there have been too many standards developed for synthetic biology and smart grid, only selected standards (approximately a dozen) were explored in detail, covering various types of standards associated with varying levels of technology elements. It is interesting to note that many of identified standards for all three cases were developed by US-based SDOs; this may be due to the fact that the US is a leader in these emerging technologies, which in turn, makes its stakeholders and SDOs active participants in the field. Notwithstanding, it is to be noted that many of them – despite their US origins – also incorporate international perspectives of standardisation through internationally joint meetings or workshops, as these are important in such globalised industries.

Only the case study of smart grid is presented in this thesis as an illustrative example of case studies due to space constraints. Focusing on standardisation issues associated with a complex system of technologies, it effectively depicts the use of the preliminary framework for systematic analyses of their dynamics with technological innovation. Studies of other cases, which are undertaken in collaboration with others, can be seen in Featherston et al. (2016).

4.3.2 Study of Case 3: Smart Grid

As advanced power grid integrating many varieties of ICTs with existing grid (NIST 2010), smart grid is expected to not only reduce inefficiencies in energy delivery, but also provide more effective management of distributed generation and storage of electric power. The development of appropriate and readily available standards is critical in supporting integration and interoperability of smart grid devices and sub-systems, because of its highly complex systems-like nature and the vast number of stakeholders involved in its operation (NIST 2010). Recognising such importance and urgency of standardisation issues in the field, NIST has identified seventy-four standards and guidelines developed by early 2014, that support interoperability of smart grid devices and systems (NIST 2014). As this list is suggested to be the most advanced and updated in the field, twelve standards have been selected from it for the case study, to demonstrate the flexibility and effectiveness of the framework. Covering a variety of functions and a range of technology elements associated with standardisation, these selected standards are listed in Table 4.2, along with their key dimensions of standardisation.

Figure 4.4 shows how the preliminary framework has been used in the case study; as smart grid is a complex system of systems integrating a vast number of devices, products, processes, and sub-systems using various technologies, the ‘system’ category in the vertical axis has been further refined based on their main domains of applications, such as generation, transmission, distribution, and operation. The framework demonstrates how various standards relevant to smart grid have supported interactions between a variety of innovation activities at different levels of technology (particularly at the ‘system’ level), by codifying and transferring different types of knowledge. They have also been developed at different times, reflecting the evolution of focus applications and systems across the innovation journey.

Many of them are compatibility / interface standards, describing how particular products and systems across various application domains need to be connected within a larger system of smart grid. Defining protocols for data exchange and communications, they ensure the successful integration and interoperability between products made by different manufacturers, as well as systems operated by different utility companies. Other standards with different functions include IEC 61850-2, containing the glossary of specific terminology and definitions used in the context of substations. Its publication at a relatively early stage of the

Table 4.2 List of selected standards relevant to smart grid

Std*	Code**	Title	What	Why	When
C1	IEC 60870-6-503	Telecontrol Equipment and Systems – TASE.2 Services and Protocol	Product, System (operation)	Compatibility / interface	2002
Q1	IEC 61850-3	Communication Networks and Systems for Power Utility Automation – General Requirements	Product, System (transmission, distribution)	Quality / reliability	2002
T1	IEC 61850-2	Communication Networks and Systems in Substations – Glossary	Product, System (transmission, distribution)	Terminology	2003
C2	IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems	Product, System (generation)	Compatibility / interface	2003
C3	IEC 61850-7-2	Communication Networks and Systems for Power Utility Automation – Basic Information and Communication Structure	Product, System (transmission, distribution)	Compatibility / interface	2003
V1	IEC 61850-6	Communication Networks and Systems for Power Utility Automation – Configuration Description Language for Communication in Electrical Substations Related to IEDs	Product, System (transmission, distribution)	Variety-reduction, Compatibility / interface	2004
M1	IEC 61850-10	Communication Networks and Systems for Power Utility Automation – Conformance Testing	Product, System (transmission, distribution)	Measurement / testing	2005
C4	ANSI C12.21	Protocol Specification for Telephone Modem Communication	Product, Production, System (operation)	Compatibility / interface	2006
Q2	ANSI C12.1	Code for Electricity Metering	Production, System (operation), Market	Quality, Measurement / testing	2008
Q3	NEMA SG-AMI 1-2009	Requirements for Smart Meter Upgradeability	Product, System (operation), Market	Quality / reliability	2009
C5	NAESB REQ18/ REQ19	Energy Usage Information	Product, System (operation), Business, Market	Compatibility / interface, variety-reduction	2010
C6	IEEE 1815	Standard for Electric Power Systems Communications-Distributed Network Protocol	Product, System (generation, operation)	Compatibility / interface	2012

* Note: Letters indicate roles and functions of standards, followed by numbers indicating the order of appearance.

** Note: See page xvi for definitions of the abbreviations used.

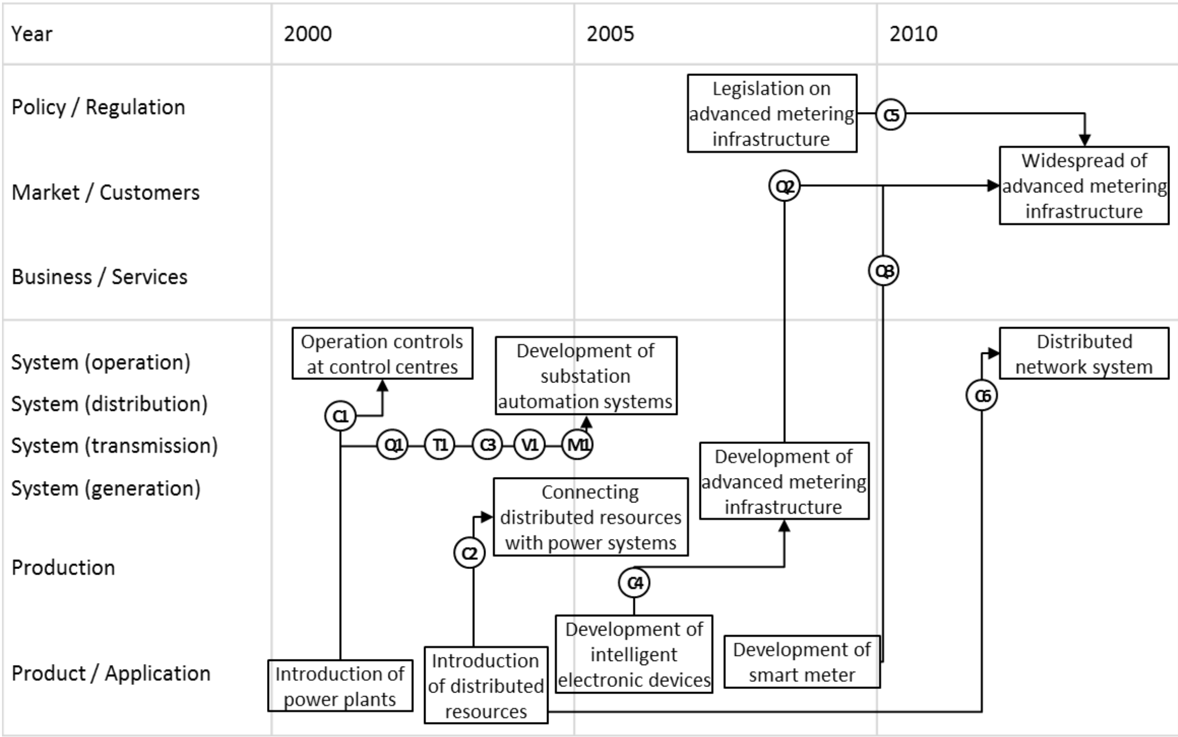


Figure 4.4 Analyses of innovation and standardisation of smart grid (see Table 4.2 for keys indicating standards)

overall innovation system suggests that common terminology needs to be established early to facilitate efficient communication among various stakeholders, as noted by Blind & Gauch (2009). IEC 61850-6 also specifies a file format for describing device configurations, increasing efficiency in communication by reducing varieties in options. In addition, IEC 61850-3 defines general quality requirements of power utility automation systems, whereas IEC 61850-10 describes recommended procedures and techniques used in conformance testing to determine whether these quality standards are satisfied. They support the innovation system of smart grid, by improving the quality of systems, as well as codifying and transmitting best practice knowledge among various application domains of the system, as argued by Tassey (2000).

4.3.3 Reflections on the Preliminary Framework

Case studies demonstrate principles of the framework for systematic analyses of the evolving role of standardisation in innovation, codifying and transferring various types of technological knowledge between diverse innovation activities. Capturing important dimensions of standardisation identified in existing frameworks (e.g., Tassey 2000, Sherif

2001, Blind & Gauch 2009) – i.e., types of technology and innovation activities involved (‘*what*’), roles and functions of standards (‘*why*’), and timing of standardisation (‘*when*’) – in a coherent and systematic way, it is shown that the roadmap-based framework helps understand overall dynamics of standardisation in the context of innovation.

The framework is also shown to overcome challenges of the functions of innovation systems approach, by disaggregating and characterising key dimensions of standardisation in greater detail (discussed in section 2.2.8). In fact, it is unlikely that each standard falls exactly and exclusively into a single category of dimensions; they rather fall into more than one category, as many standards are associated with multiple elements of technology and innovation activities, playing multiple roles at the same time. Blind (2004, p.14) also notes that “even if standards are developed just to serve one purpose they often fulfil multiple functions.” Nevertheless, distinctions between categories of dimensions are still useful for theoretical discussions to increase our understanding on complex and dynamic interplays between standardisation and innovation.

The diversity of studies in three technology sectors with different standardisation interests also demonstrates the framework’s flexibility and adaptability to accommodate a range of different types of standards associated with a variety of innovation activities throughout various stages of innovation systems. Reflecting its early stage of development, the case of synthetic biology illustrates how various terminology- and characterisation-related standardisation supports innovation activities predominantly focused on science-based research. The case of additive manufacturing highlights how various measurement / characterisation standards support research-based activities, as well as other design- and production-related activities, by facilitating communication between and within all activities within the industry. As a complex system of systems, the case of smart grid describes how various compatibility and interface standards support interactions between products and systems across diverse application domains connected within a larger system.

Although it has been demonstrated that three dimensions identified previously are all critical in understanding these complex dynamics, other aspects and characteristics of standardisation are also observed to have distinct variations across case studies. For example, standards are developed by various organisations consisting of a diverse group of stakeholders involved, from Working Groups (WGs) or Technical Committees (TCs) of official SDOs (e.g., IEC in the case of smart grid) to professional consortia (e.g., BioBricks Foundation in the case of synthetic biology), at different stages of innovation. These organisations also adopt varying approaches to standardisation in different contexts, in terms of types of deliverables and forms of specifications (e.g., international standards by IEC, and community-building standards by BioBricks Foundation), depending on the level of consensus achieved in the community. Although such issues of '*who*' and '*how*' may not be critical factors in analysing dynamics between standardisation and innovation, understanding their variations and differences may help develop more effective strategies in standardisation foresight. Yet, it appears that they have often been overlooked (if not neglected at all) in existing academic literature, while more emphases are given by practitioners. They thus need to be further explored and incorporated into the preliminary framework for more systematic and future-oriented analyses of standardisation in support of innovation.

In addition, it is suggested from the case studies that four sub-categories regarding the issue of '*what*' innovation elements are associated with standardisation need to be added or modified to improve the preliminary framework. These are discussed below.

Addition of supply network

It is observed that standardisation is also necessary for efficient transactions within supply networks, involving materials, components, equipment, and so on (Mansell 1995). For example, ASTM has developed a large number of standards (including F2924, F3001, and F3056) that outline characterisation processes and specify requirements for various stock materials used in additive manufacturing. Hence, it is appropriate to include 'supply network' as a separate sub-category for '*what*' innovation elements are relevant to standardisation.

Addition of policy / regulation

Political and legal aspects, such as industrial policy, trade and competition, and regulatory issues, are also critical in standardisation, as governments and regulators are key stakeholders in standardisation activities (Mansell 1995; de Vries 1999). For example, the Energy Independence Act of the US has played important roles in identifying needs for and developing various standards to support interoperability of smart grid devices and systems. It appears that the legislation on Advanced Metering Infrastructure (AMI) also triggered the development of NAESB REQ18/REQ19, the standard for energy usage information. Hence, 'policy / regulation' is added as a separate sub-category in the vertical axis of the framework.

Refinement of product to include application

From the case study of smart grid, it is shown to be useful to distinguish between various domains of applications – such as generation, transmission, distribution, and operation – for complex technological systems integrating a range of various products, services, and sub-systems. It helps articulate which innovation activities the particular standard transfers information and knowledge between, contributing to overall innovation systems. As they are often determined at the product level of technology, it is appropriate to add 'application' to the sub-category of 'product'.

Refinement of market to include customers

Case studies demonstrate that users and customers often provide useful perspectives in the market, as standards play important roles of legitimation (as discussed in section 2.2.3), increasing consumer confidence and potentially stimulating further innovation activities. For the case of additive manufacturing, a large number of standards are developed to support communication between developers and various user groups, such as home-additive manufacturing equipment (3D printer) users, specialist manufacturing firms, and part and tooling users. Customers and end-users are also closely involved in standardisation of smart grid, as achieving interoperability is a critical issue for gaining confidence in the market. Hence, it is important to also consider customers' perspectives in the sub-category of 'market'.

4.3.4 Further Insights from Case Studies to Justify Roadmapping Approach

Notable trends are observed from case studies that various dimensions of standardisation are interrelated with each other, as shown in existing frameworks. One of the key patterns are potential interdependencies between issues of '*what*' innovation elements are relevant to standardisation and '*why*' standards are needed, as suggested by Tassey (2000) and Sherif (2001). Each focusing on different categories of technology, case studies demonstrate the idea that standards with varying roles are associated with various types of technology with different characteristics. For example, as generic technology still emerging from fundamental science base, synthetic biology requires many standards relevant to definition of terminology and characterisation of basic units, which are necessary to reduce confusions and uncertainties associated with a new knowledge base. For the development of new production technology, there are numerous measurement / testing standards required for characterisation and testing of varieties of processes and equipments involved in additive manufacturing. As smart grid is a complex system of systems integrating existing infrastructure with new technologies, its development calls for a variety of compatibility / interface standards that allow interconnection between various devices and sub-systems.

Each at different stage of technology maturity, case studies also demonstrate that various standards play different roles at different stages of innovation processes, suggesting relationships between issues of '*why*' standards are needed and '*when*' to be standardised. This reinforces Blind & Gauch's (2009) argument that particular types of standards are needed at certain stages of innovation project. The case of synthetic biology, for example, suggests that terminology standards are developed in the early stage of innovation, linking pure basic research to oriented basic research (Blind & Gauch 2009). The case of additive manufacturing shows that measurement / testing standards appear as further technical development is achieved, bridging between basic research and applied research; whereas compatibility / interface standards provide links between experimental development and market diffusion as systems are adopted in the market, as shown in the case of smart grid.

In fact, it is suggested that five dimensions of standardisation are all closely interrelated to each other. Sherif (2001) discusses how different SDOs develop different types of standards in terms of their roles and timing of standardisation, claiming further correlations between issues of '*why*' and '*when*' standards are needed, together with '*who*' is leading standardisation. Such relationships can be partly observed from the case studies: in emerging technologies, standardisation activities are mainly led by research consortia consisting of a large group of researchers; whereas standards are developed through more consensus-based procedures by formal SDOs, in advanced technologies where there are greater involvements from the industry. In addition, they produce different types or forms of standards – i.e., technical report based on research workshops, or more formal standards with high degrees of consensus – through different approaches to standardisation, thus implying potential relationships between the issue of '*how*' standards are developed and other dimensions of standardisation.

Such complex interactions and dynamics between various issues of standardisation can be explored and observed more effectively, by using a holistic and integrated approach of the roadmap-based framework. Based on useful insights and increased understanding provided by case studies, the following section discusses how such framework can be built upon the preliminary framework for standardisation mapping (developed in section 4.2), incorporating all important dimensions of standardisation and their sub-categories in a more systematic way.

4.4 Development of Standardisation Mapping Framework

4.4.1 Additional Dimensions of Standardisation

In order to explore and identify sub-categories for additional dimensions that are useful for standardisation foresight as identified from the case studies (see section 4.3.4), a further literature review has been carried out, with particular emphases on practice literature that has been overlooked in the early literature review. These are discussed below.

4.4.1.1 '*How*' to standardise – types of deliverables and forms of specifications

As initial standards can be hard to modify or update due to time and cost requirements as well as installed-base effects (Branscomb & Kahin 1995), it is essential to decide appropriate content and flexibility of standards during its development, depending on the level of risks and uncertainties to be managed by standardisation. Hatto (2013) identifies the following categories of standard documents, according to the maturity of topic and the level of consensus achieved. It is not a comprehensive list, but rather a selective list of typical examples that are often used in the context of international or national standardisation; different terminologies and definitions may be used for standards developed by different organisations, such as other SDOs in regional / national contexts, or even consortia (these are further discussed in section 4.4.1.2). Nevertheless, similar categorisations of the type of deliverables exist, according to the level of consensus and flexibility required by standards.

- *International Standards (IS)* or *European Standards (EN)* are developed for topics with the highest level of maturity and a high degree of consensus among various member countries.

- For topics that meet certain criteria, but are seen to be premature, still underdeveloped, or have not reached a sufficient consensus, *Technical Specifications (TS)* are typically developed to make specifications available for evaluation, and accumulation of further knowledge and experience to be incorporated into a full standard later.

- *Publicly Available Specifications (PAS)* are developed for subject matter that is at an even earlier stage of development or consensus-building, but in urgent market needs for normative documents, encouraging to speed up standardisation in areas of rapidly evolving technology.

- *Workshop Agreements (WA)* can be generated within the context of a workshop, as fast deliverables for emerging areas. Often linked to research and innovation, they can be developed even without any relevant TCs developing standards.

- Sometimes, *Technical Reports (TR)* are prepared as informative documents that do not contain any requirements, but to provide background to a technical area or to assist with the application or interpretation of a full standard.

These documents can be written in various formats concerning embodiment of standards, including codes, specifications, guides, and processes (Sivan 1999; ASTM 2012; Spring et al. 2014). Definitions of these formats vary among different standards organisations; nevertheless, they fall into one of the following categories, depending on the form of specifications:

- Often based on product experience, *performance* (also called as *performance*- or *outcome-based*) *standards* specify desired outcomes or performance levels, allowing flexibility in product or service design while still meeting the performance requirements of the standard (de Vries 1999; Allen & Sriram 2000; Tassey 2000). For example, minimum standards of quality and safety for products may be specified to promote greater consumer protection (BERR 2008).

- *Solution-describing* (also called as *process-oriented*, *prescriptive*- or *design-based*) *standards* provide detailed descriptions or precise specifications for exactly how designs or solutions could achieve these outcomes in a consistent and repeatable way (de Vries 1999; Allen & Sriram 2000; BERR 2008), hence are much more restrictive (Tassey 2000). Many compatibility / interface standards for ICT are of this type (de Vries 1999).

4.4.1.2 ‘*Who*’ is leading and involved in standardisation – types of SDOs and stakeholders

Many scholars identify authorship, sponsor, origin, or source of standards as important dimensions of standardisation (e.g., Bonino & Spring 1999; Sivan 1999; Blind 2004). Before discussing this issue of ‘*who*’ is leading standardisation activities, it is necessary to first distinguish between de facto and de jure standards according to their origins, either in the market place or the strategic efforts of recognised SDOs.

- *De facto standards* are usually driven by market forces, either voluntarily formed from wide market acceptance or established through standard battles (Branscomb & Kahin 1995; Allen & Sriram 2000; Tassey 2015). Rather than an open, collective consensus process, they often begin as industry or proprietary standards developed by a specific organisation for internal uses (within companies or their supply chains) (Bonino & Spring 1999; Coallier & Robert 2006). While de facto standards may facilitate innovation through standards competition, there is a danger that privately profitable but socially undesirable technologies become standards (Wang & Kim 2007). Examples of de facto standards include Windows operating system, architecture of the IBM PC, and QWERTY keyboard (OCST 1993; Allen & Sriram 2000; Coallier & Robert 2006).

- *De jure standards* are generally developed and approved by recognised SDOs through the formal consensus-based process (Branscomb & Kahin 1995; Allen & Sriram 2000; Hatto 2013). Although some people prefer to limit de jure standards to standards that have the force of law, it is more appropriate to call them mandated, mandatory, or regulatory standards (David & Greenstein 1990; Allen & Sriram 2000; Blind 2004). The open review process of de jure standards generally improves definition and reduces unnecessary costs of competition (Libicki et al. 2000; Wang & Kim 2007). Some literature also call them (voluntary) consensus, committee, or official standards (David & Greenstein 1990; Bonino & Spring 1999; Spring et al. 2014).

De jure standards can be further categorised according to the type of SDOs developing the standard. There are various types of SDOs at different levels with different focus and expertise, depending on their nature and characteristics, including the following:

- Formally recognised by a government authority, *Formal Standards Organisations (FSOs)* can be national SDOs (e.g., ANSI, BSI, DIN, and AFNOR), regional SDOs (e.g., CEN, CENELEC, and ETSI), or international SDOs (e.g., ISO, IEC, and ITU); standards developed by them are called national, regional, or international standards, respectively (de Vries 1999; Hatto 2013). Typically operating through national or governmental representation (at least in terms of approval processes) rather than organisation or individual representations (Hatto 2013), robust procedural rules for standardisation are well documented and followed, ensuring transparency and due process for all participants (Biddle et al. 2012).

- As professional or specialist organisations in particular sectors or disciplines, *Sectoral or Specialised Standards Organisations (SSOs)* can also publish standards at national, regional, or international levels (de Vries 1999). Standards set by such SSOs may be technologically superior, as their members participate as individual professionals rather than representatives of any groups, thus are insensitive to industry competitive issues (OTA 1992). SSOs vary considerably in terms of their format, process, participation, and outputs, and include both non-profit, industry-driven SDOs (e.g., ASTM), and professional engineering or scientific associations (e.g., IEEE) (de Vries 1999; Coallier & Robert 2006; Biddle et al. 2012).
- Recently, new forms of SDOs such as *industrial consortia or fora* (e.g., W3C, OASIS, and IETF) tend to develop standards, in response to demands for their faster development; this is especially the case in ICT-related domains, where complex anticipatory standards are needed for technologies with shorter lifecycles (Weiss & Cargill 1992; Coallier & Robert 2006). Often focusing the work on well-defined projects, they may limit participation and follow own operational procedures (Sherif 2001; Biddle et al. 2012). Research consortia and initiatives (e.g., BioBricks) are also emerging as new forms of SDOs formed by like-minded interests on emerging areas of research.

There are various stakeholders participating in standardisation activities at these SDOs. ISO TC207 (Technical Committee on Environmental Management, 2006) defines the following six categories of stakeholders with interests in standardisation. The importance of such varied participants is identified in various literature (e.g., Yoo et al. 2005; Blind & Gauch 2009):

- *Consumers*: Standards are important for consumers to benefit from high-quality and cheaper products, as well as product interoperability (OTA 1992; Biddle et al. 2012). Consumer organisations give special attention to quality, safety, certification, and conformity assessment of products (de Vries 1999).

- *Government*: Government or other public agencies play various roles in standardisation (see Table 4.3 for details) for a variety of reasons, from stimulating improvements in national standardisation infrastructures to using standardisation for specific governmental tasks (Repussard 1995; de Vries 1999; OTA 1992; Swann 2010)
- *Industry (companies)*: Producers use standards in order to differentiate their products from competitors or get market success for their products (OTA 1992; de Vries 1999). Users, on the other hand, buy products affected by standards, or use standards for their production processes; they can be either direct or indirect users, depending on the importance of contents of standards (de Vries 1999).
- *Labour*: As workers are affected by standards at the workplace, representative workers' organisations, such as trade unions, may participate in standardisation (ISO TC207 2006).
- *Non-Governmental Organisations (NGOs)*: Independent not-for-profit associations may have public interest objectives in standardisation (ISO TC207 2006).

Table 4.3 Roles of government in standardisation

Roles	Details	References
Educator	Education and promotion to facilitate the standards setting process	Repussard 1995; Garcia 2005
Convenor / coordinator / broker	Bringing together players, convening their diverse interests, and facilitating cooperation among them	Branscomb 1995; Garcia 2005; NIST 2001
Funder	Financially supporting particular standardisation activities or R&D to prepare technical input into standardisation	Branscomb & Kahin 1995; Repussard 1995; Garcia 2005; NIST 2001
Rule maker	Setting laws on standardisation, to establish its infrastructure / systems	De Vries 1999; Garcia 2005
Developer / advisor	Conducting or investing in R&D to support standards development	Branscomb & Kahin 1995; Garcia 2005; NIST 2011
Participant	Participation of government experts in standardisation activities as a member of SDOs	Repussard 1995; NIST 2011
Regulator / adopter	Implementing or referencing to particular standards through regulation / legislation	Branscomb & Kahin 1995; De Vries 1999; NIST 2001
Consumer	Using standards for specific governmental tasks or procurement	De Vries 1999; Garcia 2005
Interested observer	Monitoring and assessing standardisation activities on an ongoing basis	NIST 2011

- *Service, support, research, and others*: Professionals, consultants in particular, as well as organisations for testing, certification, and accreditation may also have interests in standardisation (de Vries 1999). Scientists and engineers, for example, provide sound technical base for standardisation, and also benefit from more accurate standards for measurement and instruments to take these measurements (OTA 1992).

These stakeholders have different interests and motivations to be involved, thus taking different roles in standardisation, including advocate, architect, critic, facilitator, and guru, as identified by Umapathy et al. (2012). Blind & Gauch (2009) also note that different stakeholders participate in standardisation at different stages of the innovation process.

4.4.2 Standardisation Mapping Framework (Ver.1)

These two additional dimensions of standardisation – '*how'* and '*who'* – are incorporated in the preliminary framework (shown in Figure 4.2), resulting in the standardisation mapping framework (ver.1) (see Figure 4.5). As they are additional strategic considerations rather than critical dimensions for analysing complex dynamics with innovation, they are included as supplementary information in prose formats, using either text boxes (as shown in Figure 4.5) or separate tables (as shown in Table 6.1). By integrating all important dimensions of standardisation identified by previous models in existing literature – i.e., '*what*', '*why*', and '*when*' (Tassey 2000; Sherif 2001; Blind & Gauch 2009) – as well as additional strategic dimensions, it provides a more comprehensive and systematic framework for standardisation in the context of technological innovation. It can thus be suggested that the framework, by effectively representing the multi-dimensional nature of standardisation and how these dimensions interact with each other, can be used for systematic and future-oriented analyses of complex and dynamic interplays between standardisation and innovation.

It also appears that the current standardisation mapping framework incorporates most of the important questions that are often used to describe any forms of human activity – i.e., *what*, *why*, *when*, *how*, and *who* – ensuring a systematic and complete identification of important dimensions of standardisation. It is appropriate to neglect the issue of '*where'* standards are to be developed and used, as it is duplicative with other issues. For instance, different countries and regions where standardisation is carried out have different implications for the standardisation landscape, such as different types and roles of SDOs leading standardisation, which, in turn, also decide what types of standards documents are developed and delivered. As these vary significantly depending on national and regional contexts, including the culture and history of their institutional systems, it is suggested to be the best to keep distinctions simply regarding the issues of '*how*' and '*who*'. Nevertheless, it appears that all important aspects of standardisation in the context of technological innovation are reasonably covered by other five dimensions.

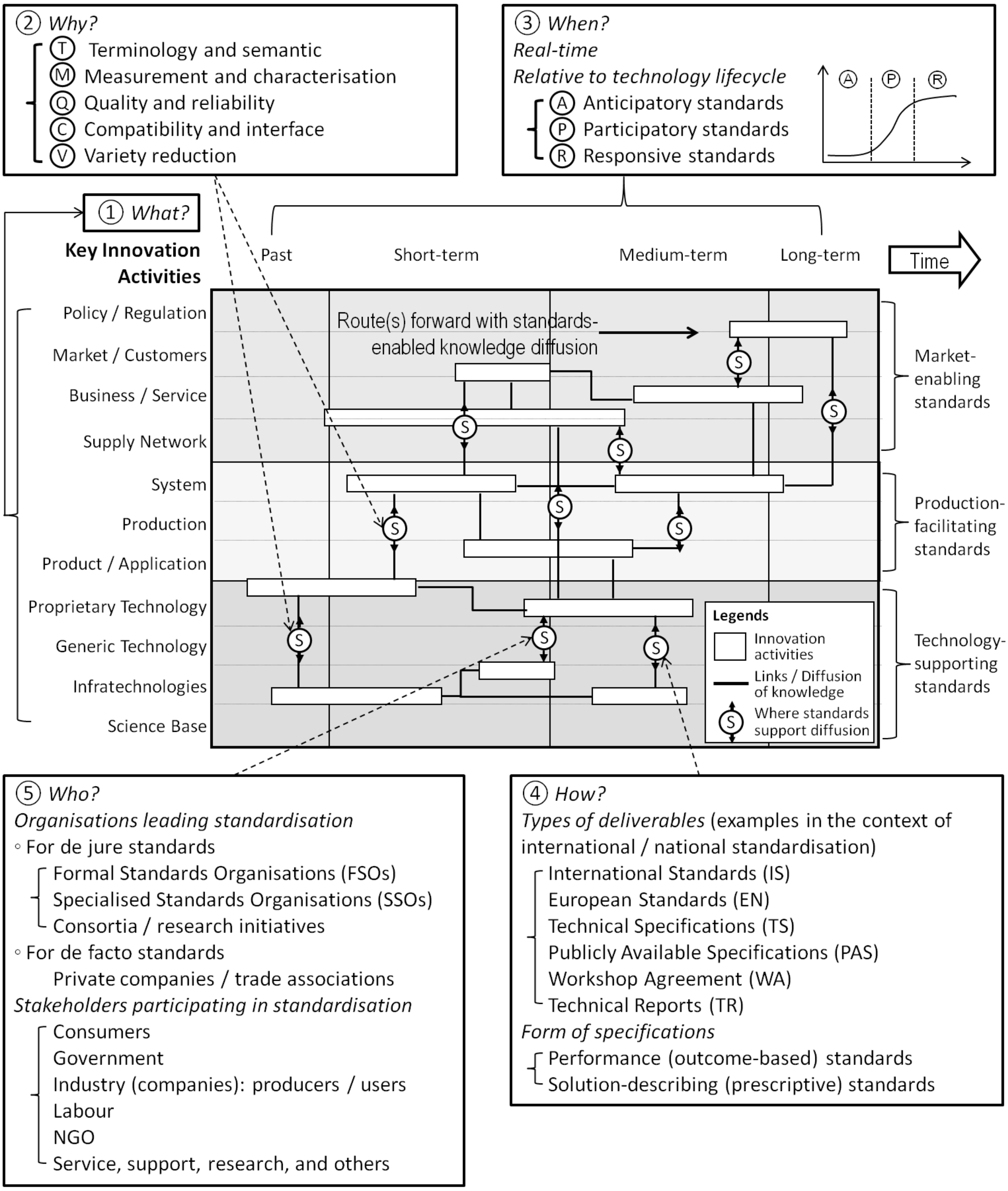


Figure 4.5 Standardisation mapping framework (ver.1)

4.4.3 Other Challenges and Issues to be Explored

Timing of particular types of standards

Case studies of recent standardisation in three different emerging sectors provide useful 'proof of concept' of the proposed framework, illustrating how various issues of standardisation in the context of technological innovation can be captured more systematically. Although they highlight most features and issues addressed by existing theories and models (e.g., Tassey 2000), the timing of particular types of standards are not reflected as clearly or as linearly as suggested by Sherif (2001) or Blind & Gauch (2009). This is possibly due to: the nonlinearity of technology development (as acknowledged by Blind & Gauch (2009)), the different timeframe between identification of standards needs and their publication because of long time of standards development, and the variety of technologies within each field at different stages of development. Such issues need to be further explored in subsequent studies, to improve the proposed framework, and to enhance our understanding of complex and dynamic interplays between standardisation and innovation; it is further discussed in section 6.2.2.

Bundling of standards

It is observed from case studies that many standards related to smart grid are bundled together, i.e., various types of standards (playing different roles and functions) that are interrelated to each other are treated as subsections of a large umbrella standard. For example, IEC 61850 series (for communication networks and systems for power utility automation) incorporates standards with various roles, including terminology (IEC 61850-2), measurement and testing (IEC 61850-10), quality and reliability (IEC 61850-3), compatibility and interface (IEC 61850-7-2), and variety-reduction (IEC 61850-6). This is suggested to be due to the increasing complexity of technologies and systems that are interrelated to each other. This is further explored and discussed in section 6.3.1.

4.5 Concluding Remarks

Providing a holistic and integrated perspective of complex systems, a roadmap-based framework is suggested to be useful in analysing overall dynamics between standardisation and technological innovation. Incorporating '*what*', '*why*', and '*when*' aspects of standardisation – i.e., technology and other innovation elements relevant to standardisation, roles and functions of standards, and their timing of development and implementation – with long-term systems perspectives, a preliminary framework for standardisation mapping is developed and tested in three different technology domains. Case studies demonstrate the usefulness of the roadmapping approach in capturing these dimensions, as well as observing interrelationships and dependencies between them, highlighting 'mediating' roles of standardisation. Case studies also suggest that additional strategic dimensions of standardisation – i.e., '*how*' standards are developed and '*who*' is leading and involved in standardisation – need to be incorporated in the preliminary framework. By revisiting academic and practice literature, a standardisation mapping framework (ver.1) is thus developed, allowing more systematic and future-oriented analyses of standardisation in support of innovation. The next chapter will explore how to actually use the proposed framework in practice for strategic foresight of standardisation.

5. DEVELOPMENT OF PROCESS MODEL

This chapter[*] presents a systematic process model for using the '*standardisation mapping framework*' – outlined in the previous chapter – to develop standardisation strategies in practice. Due to the increasing complexity of modern technologies and the variety of perspectives to be addressed in standardisation, a more systematic and structured process for gathering various inputs from a diverse group of stakeholders is needed for strategic foresight analyses of standardisation. As the proposed framework is essentially based on a roadmapping framework, existing literature on the general process of strategic roadmapping is first reviewed, providing a preliminary, baseline model for case studies. Case studies are then conducted, exploring detailed activities and practices adopted in a number of existing standardisation roadmapping exercises, which provide insights and implications for more effective and systematic processes. Incorporating useful practices and lessons learnt from these, an improved process model for standardisation foresight is presented, effectively addressing issues and challenges associated with standardisation of modern technologies that are becoming more complex, interdisciplinary, and fast-evolving.

5.1 Introduction to Strategic Roadmapping Process

Despite the potential utility of the standardisation mapping framework developed in Chapter 4 for systematic analyses of standardisation in support of innovation, there remain significant challenges in using this framework for future-oriented analyses to support the development of standardisation strategies. Such challenges are due to the increasing complexity and uncertainty associated with standardisation of modern technologies that are global and

[*] Part of the research contained within this chapter has been published as J. Y. Ho and E. O'Sullivan (2016) Strategic standardisation of smart systems: A roadmapping process in support of innovation. *Technological Forecasting and Social Change* (In press)

interdisciplinary, yet there are intrinsic limitations of the roadmap-based framework for addressing issues outside the technological system under consideration. Although various issues, such as innovation systems in other countries, markets with different main applications, and related technological domains, all influence standardisation of a particular technological system, these factors are not appropriately captured in the proposed standardisation mapping framework. In addition, further challenges exist as increasing convergence of technology requires inputs from a variety of sources and stakeholders – including those from other related domains – for effective standardisation foresight. More research is thus needed to explore how such challenges can be addressed in using the standardisation mapping framework for systematic and future-oriented analyses of standardisation.

As the framework is essentially based on the strategic roadmapping approach, examining how existing standardisation roadmapping exercises are carried out in practice may provide useful insights for more systematic processes of structuring and managing foresight analyses. The practice review in section 2.4.5 shows that roadmapping practices have been actually adopted for effective anticipation and management of standardisation in a number of interdisciplinary technologies. Detailed steps and tools adopted during the development of these roadmaps – e.g., how to gather benchmarking data, how to engage various stakeholders, and how to structure and organise collected information relevant to factors outside the technological system it considers – as well as sequences of these activities, may suggest effective ways of addressing challenges with standardisation foresight. Before exploring processes of existing standardisation roadmapping practices in more detail, it is appropriate to first review relevant academic and practice literature on general roadmapping processes.

5.1.1 General Process of Roadmapping

There are no hard and fast rules on how to perform strategic roadmapping, and the process differs depending on the purpose and type of roadmap (Phaal et al. 2010). Nevertheless, the following broad steps are presented in various literature as a general guideline for roadmapping processes (Emerging Industries Section 2001; Groenveld 2007; Phaal & Muller 2009):

- *Initiation and planning*: to define scope, objectives, and boundaries of the roadmap, and identify participants, structure, and process of developing the roadmap.
- *Input and analysis*: to capture, structure, and share relevant knowledge.
- *Synthesis and output*: to create the roadmap through convergence and synthesis, and implement to fulfil the objectives.
- *Follow-up*: to review and update the roadmap; this is very important, as roadmapping is an ongoing learning process, rather than a single, one-off activity.

Detailed procedures of each phase also differ depending on various factors. Nevertheless, as the roadmapping is essentially a technique used in strategy development, they usually follow the general strategy process. Comparing published process models for business and technology strategy, Phaal et al. (2010) propose a generalised strategy process model comprising of the following steps:

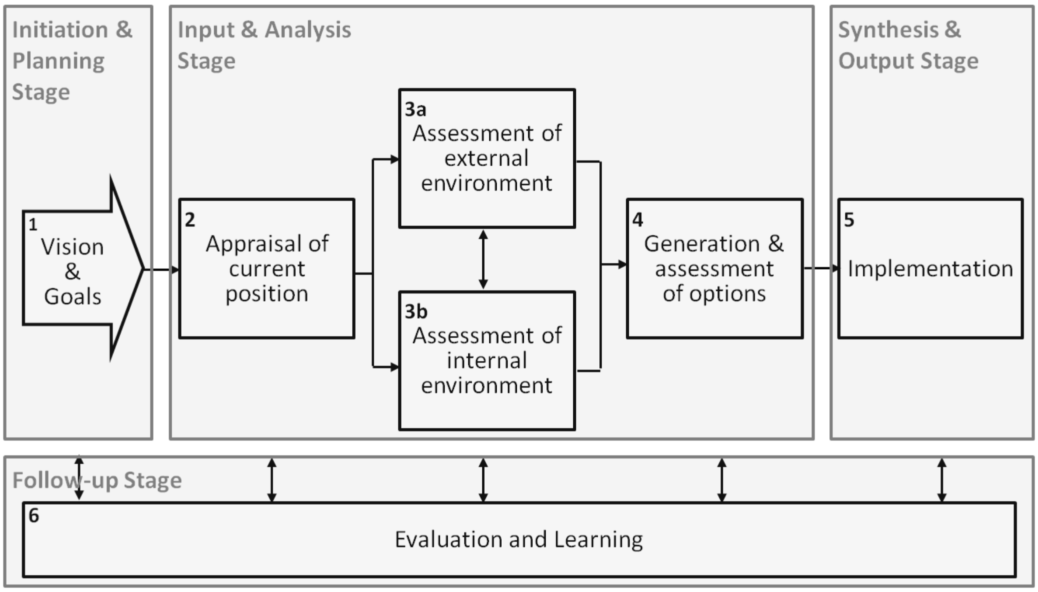
1. *Vision and goals*: to establish a sense of direction, in terms of a future vision and goals.
2. *Appraisal of current position*: to collate and assess information currently available, relating to current and historical strategies, activities, and performance.

3a. *Assessment of external environments*: to collect and assess information relating to external factors, issues, and drivers, to identify opportunities and threats.

3b. *Assessment of internal environments*: to collect and assess information relating to internal resources, capabilities, and constraints, to identify strengths and weaknesses.

4. *Generation and assessment of strategic options*: to generate strategic options, identify gaps, and assess and select the options to derive strategic plans.
5. *Implementation*: to put the strategic plan into action.
6. *Evaluation and learning*: to review outcomes and disseminate results.

This strategy process model developed by Phaal et al. (2010) can be mapped against general steps for roadmapping processes discussed previously, emphasising the strategic purpose of roadmapping exercises; this is illustrated by author in Figure 5.1. As a schematic representation of the general strategic roadmapping process, it may also be used as a preliminary, baseline model of the process for using standardisation mapping framework (developed in Chapter 4) for standardisation foresight.



(based on Phaal et al., 2010)

Figure 5.1 Preliminary process model for standardisation foresight (ver.0)

5.1.2 Roadmapping Process for Standardisation Foresight

Although above steps closely represent the general process of roadmapping for business strategies, further challenges exist in roadmapping to develop standardisation strategies at a policy level with long-term perspectives. As such exercises often require system-level strategy development covering broader issues of collective interests (e.g., infrastructure as discussed by Tassey (2005)), they need to effectively draw on previous roadmapping (or other similar foresight) exercises, which generally address particular aspects of the system or take the perspective of a particular group of innovation actors. Roadmapping for standardisation foresight also involves a diverse group of stakeholders representing various perspectives, including innovation actors with technical knowledge and resources required for standardisation, as well as those who lack such knowledge but are still affected by its outcomes (e.g., small companies, consumers, regulators, and government) (Yoo et al. 2005; Swann 2010; Blind 2013). In addition, the systemic, fast-evolving, and interdisciplinary nature of modern technologies has led to increased complexities in strategic management of standardisation, as discussed in section 2.4.3. Because of such challenges involved, rigorous planning and governance of roadmapping exercises are required for more effective foresight processes using the standardisation mapping framework.

In this regard, investigating actual processes of existing standardisation foresight exercises may provide useful insights to develop an improved process model for future-oriented analyses of standardisation. In particular, roadmap-based strategic exercises have been the most widely adopted for standardisation foresight (as discussed in section 2.4.5) due to its systems-based nature, effectively identifying key gaps in knowledge and their contexts (Phaal et al. 2010). Its systematic nature also makes it an effective way to frame standardisation strategies within a broader context of technology strategies or existing foresight for innovation systems, allowing to make the best use of standardisation (Moreton 1999). In addition, the consensus-based nature of the roadmapping approach is particularly useful in standardisation, which is essentially a consensus-building activity of various parties involved. Consequently, a number of standardisation roadmaps have been developed in various areas where standardisation plays critical roles, including ICT, additive manufacturing, smart grid, cloud computing, electromobility, and smart manufacturing (NIST 2010; Hogan et al. 2011; NPE 2012; NIST 2013; TTA 2013; DKE 2014). These are further explored in the following section, leading to further development and improvement of the general roadmapping process model for valid and appropriate processes of standardisation foresight using the standardisation mapping framework developed in Chapter 4.

5.2 Case Studies for Testing and Developing Preliminary Process Model

In order to examine the applicability and basic utility of the baseline model (shown in Figure 5.1) and build on it for more effective processes of standardisation foresight using the standardisation mapping framework (developed in Chapter 4), cases of existing standardisation roadmapping exercises have been analysed. It can provide not only insights into issues and challenges associated with standardisation foresight, but also further implications for effective processes of managing and organising such foresight analyses.

5.2.1 Overview of Case Studies

Six recently developed standardisation roadmaps, spanning various technology domains in different countries, have been reviewed; they highlight diverse issues and challenges of standardisation foresight in modern technologies, which are summarised in Table 5.1.

Table 5.1 Existing standardisation roadmapping exercises

Case	Developing Organisation	Participants (order of %)	Main Types of Standards	Challenges in Strategic Management and Foresight Analyses of Standardisation
Case 4: ICT Standardisation Strategy Map (TTA 2013)	Telecommunications Technology Association (TTA) of Korea	Research laboratories, Industry, Academia, Government, SDOs	Technology-supporting standards, Compatibility/ interface standards	Due to the nature of interdisciplinary areas: - all-encompassing approach required for cross-level / cross-domain strategies - participation and coordination of various organisations with relevant standardisation activities
Case 5: Measurement Science Roadmap for Metal-Based Additive Manufacturing (NIST 2013)	NIST Intelligent Systems Division of the Engineering Laboratory	Industry, Research laboratories, Academia, Government, SDOs	Production-facilitating standards, Measurement/ testing standards	Due to a wide variety of applications and multiplicity of technologies involved: - involvement of and communication between a large number of stakeholders with different expertise and perspectives - collation and usage of existing supporting documents
Case 6: NIST Framework and Roadmap for Smart Grid Interoperability Standards (NIST 2010)	Smart Grid and Cyber-Physical Systems Program Office of the US	Industry, Research laboratories, Government, SDOs, Academia	Technology-supporting/ market-enabling standards, Compatibility/ interface standards	Due to the nature of a complex system of systems: - involvement of and communication between a large number of stakeholders with different expertise and perspectives - cooperation among various SDOs developing related standards - integration of existing and emerging systems
Case 7: The German Standardisation Roadmap for Electromobility (NPE 2012)	National Platform for Electromobility (NPE) of Germany	Industry, Government, Academia, Research laboratories, SDOs	Technology-supporting standards, Compatibility/ interface standards	Due to the integration of two separate domains: - coordination and integration of standardisation activities required for new points of contact and interfaces - participation of a variety of actors from different sectors
Case 8: NIST Cloud Computing Standards Roadmap (Hogan et al. 2011)	NIST Cloud Computing Standards Roadmap Working Group	Industry, Government, Research laboratories, Academia	Technology-supporting standards, Compatibility/ interface standards	Due to the involvement of various organisations with relevant standardisation activities: - participation and coordination of these organisations - collation and usage of existing supporting documents
Case 9: The German Standardisation Roadmap Industrie 4.0 (DKE 2014)	German Commission for Electrical, Electronics & Information Technologies of DIN and VDE (DKE)	Industry, Academia, SDOs, Government	Technology-supporting / production-facilitating standards, Compatibility/ interface standards	Due to the nature of a complex system of systems: - involvement of and communication between actors from different disciplines - cooperation among various SDOs - integration of existing and emerging systems - all-encompassing approach required for cross-level / cross-domain strategies

Each developed in different contexts – in terms of technology maturity, application characteristics, and national contexts – the selected roadmaps had different issues associated with, and thus took different approaches to, standardisation foresight. Detailed processes of developing these roadmaps were then analysed against the baseline model (shown in Figure 5.1). Examining specific activities and practices undertaken in each step provided implications for developing a more effective process model for structuring, managing, and governing standardisation foresight exercises. Performed in two rounds of iteration, processes of developing Cases 4 through 7 were analysed in detail in the first round of case studies. Then, Cases 8 and 9 were briefly explored (using limited amount of secondary sources) for the purpose of testing and refinement; no additional features were identified during these studies, demonstrating the relative stability of the process model (see section 3.6.2 for details).

Table 5.2 shows the number of data sources for each case study. Mostly qualitative data were collected through the desk research of documentations, such as standardisation roadmaps and official reports, which provided reliable and detailed information on standardisation roadmapping exercises. Thirty-two interviews with experts who have been involved in developing these roadmaps were also carried out, in order to help understand the background and details of major activities, which are difficult to access through document sources alone; a large number of interviews were thus conducted particularly for Case 4, complementing lack of secondary sources available. Interviewees were selected from various organisations – i.e., standards organisations (ten), research laboratories (nine), industry (six), academia (six), and government agencies (one) – ensuring the representation of varied perspectives; see Table A.2 in Appendix A for detailed profiles of interviewees.

While studies were carried out in a range of technology domains demonstrating flexibility and adaptability of the roadmapping approach, only studies of Case 4 and Case 5 are presented here as illustrative examples due to space constraints. Based on rich information due to easy access to data, they provide contrasting examples covering different types of standards and addressing various issues and challenges associated with standardisation. Studies of other cases are summarised in Table 5.3 on p.100; detailed analyses of Case 6 and Case 7 can be also found in Ho (2014) and Ho & O'Sullivan (2016).

Table 5.2 Number of data sources used for case studies

	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
No. of interviews	22	2	6	2	0	0
No. of documents	4	37	39	20	5	1

5.2.2 Study of Case 4: ICT Standardisation Strategy Map by TTA of Korea

According to many interviewees, mainly from government and standards organisations in Korea, standards have long been understood as significant national resources to secure international market access, as Korea's economy heavily relies on exports. They are especially important in the ICT industry, where compatibility and interoperability are essential for systems to function properly. Recognising such importance, Korea has been developing the ICT Standardisation Roadmap since 2003 – which later changed its name to ICT Standardisation Strategy Map in 2010, with more focus on strategies – in order to support effective standardisation in a number of 'focus technology areas'. Funded by government, TTA – i.e., Korean industry association responsible for developing voluntary industry standards for wide areas of ICT – leads the roadmapping exercise every year, which provides a detailed time plan of what standardisation strategies and relevant activities are to be adopted by which organisations, noted multiple interviewees. (TTA 2013)

Figure 5.2 outlines the overall process of developing the 2013 ICT standardisation strategy map, based on expert interviews and documental analyses, using the preliminary process model shown in Figure 5.1. It was actually developed more iteratively rather than being locked into a particular structure from the beginning, and detailed (sub-)processes varied depending on focus technology area. Nevertheless, the general approach followed the four basic stages identified earlier: planning, analysis, synthesis, and follow-up.

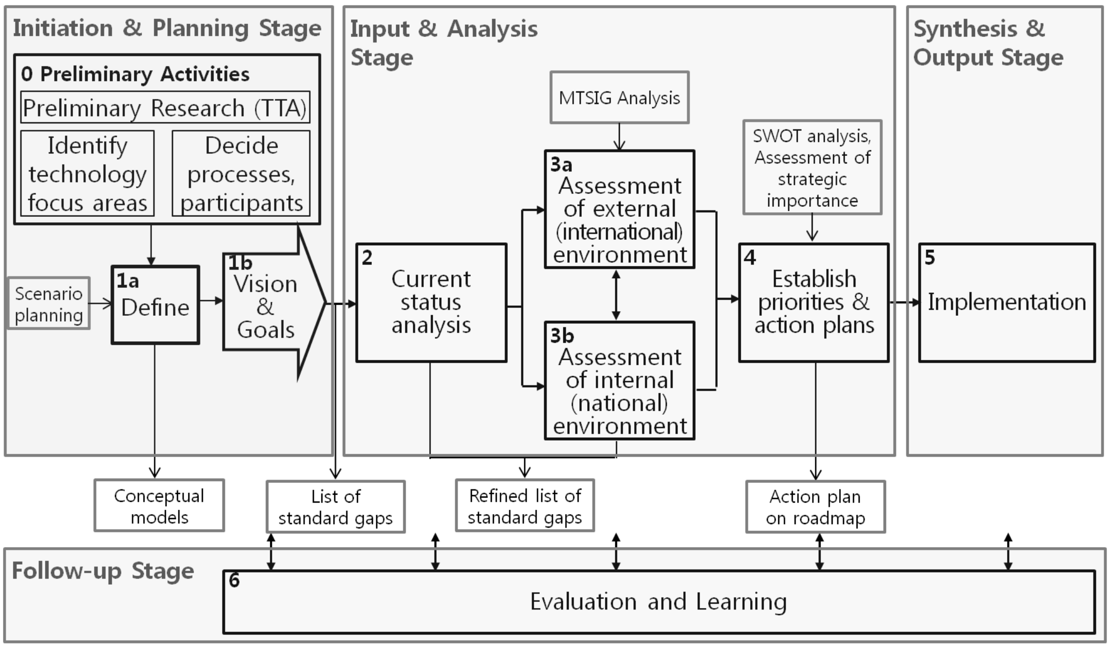


Figure 5.2 Process of developing ICT standardisation strategy map by TTA of Korea

Step 0: Preliminary activities

A number of preliminary activities were carried out, before the actual roadmapping process started. First, the administration team at TTA conducted preliminary research, in order to identify potential areas of standardisation needs through keyword research, based on current standardisation activities of major SDOs, technological trends, government policies, and standardisation proposals submitted by researchers, according to an interviewee. In 2013, 31 focus areas were selected and categorised into five groups (convergence service, contents/platform, communication, TV/broadcast, and information security); for each focus area, participants of roadmapping were determined from the experts' pool, along with the process and structure of developing the roadmap (TTA 2013).

Step 1a: Definitions

The first step of developing the roadmap was to define each focus area and identify its vision and goals. Defining the technology helped reduce confusion and ambiguity, and gave an overall view of the system under consideration. Planning service scenarios and developing conceptual models sometimes facilitated this process. According to interviewees, scenario planning were used to analyse how systems need to be developed in order to provide intended services to customers; while conceptual models allowed a better understanding of overall systems' structures from a more holistic view, by identifying domains and actors, their functions and characteristics, as well as their relations to each other. They usually existed as drafts in the beginning, and were often revised and updated at later stages, reflecting additional inputs and analyses throughout the roadmapping process, noted a few interviewees.

Step 1b: Vision and goals

Visions, objectives, and expected outcomes of standardisation were then defined in order to guide the direction of roadmap; according to interviewees, these works were often collaboratively conducted by co-editors, and reviewed by a chief editor towards the end of roadmapping. Once the vision and goals were identified, participants listed detailed areas of technology with potential standardisation needs (TTA 2013). Most interviewees noted that identifying standardisation gaps to be addressed is often an obvious task, as participants were usually experts in their fields of standardisation, so aware of key trends and issues in terms of technology and standardisation. According to an interviewee, since many participants were also involved in TTA project groups or forums that actually work on the development of standards, general consensus could be easily reached on which areas need more attention, and those are identified as standardisation gaps.

Steps 2 and 3: Analyses of current status and assessment of environments

For each standardisation gap identified, analyses of current status and assessment of (inter) national environments were carried out in terms of Market, Technology, Standards, Intellectual property, and Government policies and key industry environments (thus called MTSIG analysis). According to interviewees, work was usually distributed among participants according to their detailed areas of expertise; however, participants from research organisations – mainly from the Electronics and Telecommunications Research Institute (ETRI) – tended to take the main responsibility for writing contents, while the others participated by giving feedback. As a result, analyses and assessment generally focused on technology and standardisation perspectives, based on researchers' knowledge and insight, as well as information from publications of SDOs. Throughout these steps, the list of standardisation gaps were sometimes modified, as analyses of current trends and issues revealed new information. (TTA 2013)

Step 4: Establish priorities and action plans

According to interviewees, the next step involved analyses of strategic importance and the urgency of each standardisation gap, to prioritise them and develop necessary action plans. Participants conducted SWOT analyses (i.e., analyses of Strengths, Weaknesses, Opportunities, and Threats), along with assessment on the strategic importance of each standardisation gap, based on various criteria such as national competence, contributions to international standardisation, potential for intellectual properties, impacts on industry, and alignment with government policies. Based on these evaluations, strategic positions – such as shaper, co-shaper, reserver, or adopter – were determined for each standardisation gap, with time plans for which SDO to develop corresponding standards. Once strategies were developed for individual gaps, they were reviewed by other co-editors in a meeting, to ensure objective and consistent assessment, particularly among areas that were closely related to each other. They were then collated to form a medium-term roadmap, which was later reviewed by chief editors and reviewers from other focus areas as well. (TTA 2013)

Step 5: Implementation

The final long-term roadmap was developed by consolidating medium-term roadmaps developed by each focus areas' group, and adding layers of relevant products and services, and infrastructure (see Figure A.1 in Appendix C for an example). It was published after review in an open workshop, where other standardisation experts and members of the public were invited to comment on the final output. According to an interviewee, the published roadmap provided not only useful sources of information as documents with collective insights, but also important guidelines for government and industry to develop their standardisation and R&D strategies, including making decisions for funding. (TTA 2013)

Step 6: Evaluation and learning

According to interviewees, TTA conducted post-survey, where participants were asked for their opinions on the overall process of the roadmap development, and used this information to revise and improve the structure, process, and management system of roadmapping exercises in the following year.

5.2.3 Study of Case 5: Measurement Science Roadmap for Metal-Based Additive Manufacturing by NIST of the US

Additive manufacturing faces particular challenges, due to a wide variety of applications and multiplicity of technological approaches, processes, and materials associated with it; systematic approaches are thus needed to help the community coalesce and coordinate around strategy development for supporting this emerging technology. A number of supra-firm strategic roadmaps have recently been developed around the world, identifying priority actions to accelerate its deployment in various applications and technical focus areas (e.g., NIST 2013; Bourell et al. 2009). In particular, a recent roadmap developed by NIST (2013) focuses on measurement science and standards issues of additive manufacturing, building on established understanding of various stakeholders to achieve coherence in their activities.

Figure 5.3 represents the overall process used to develop the measurement science roadmap for metal-based additive manufacturing. Particular emphasis is put on how to benefit from previous analyses to enhance efficiency of the process, through various preliminary activities.

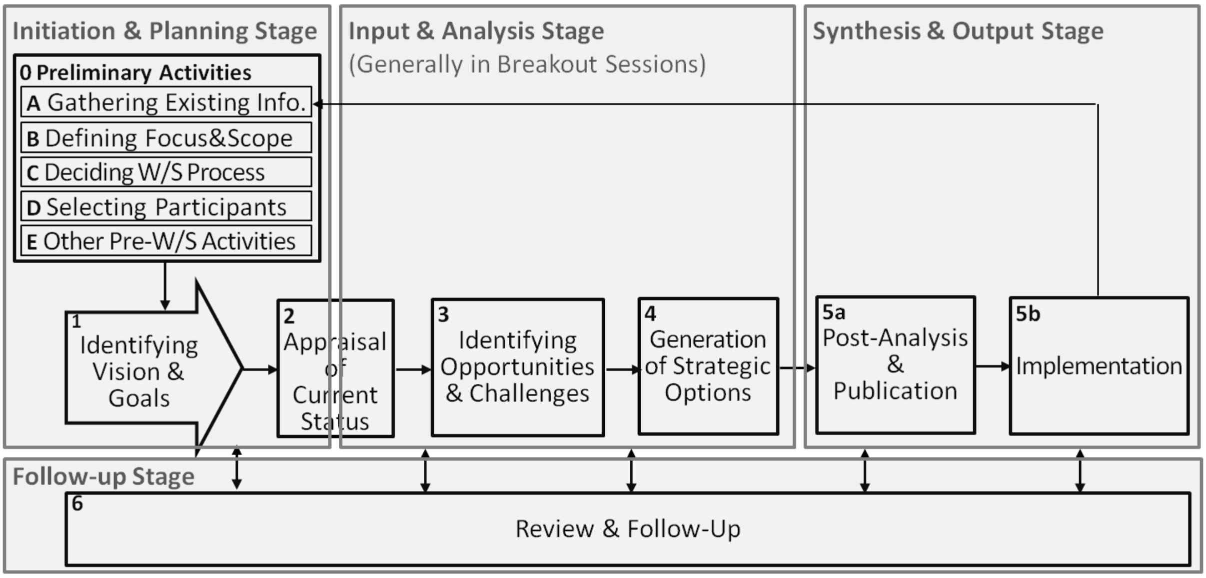


Figure 5.3 Process of developing measurement science roadmap for metal-based additive manufacturing by NIST of the US

Step 0: Preliminary activities

Preliminary activities during the planning and initiation phase were highlighted as an important first step of developing the roadmap. They generally involved planning and preparing for workshops, which played a key role in the roadmapping exercise.

Step 0a: Gathering existing information

Once the objectives and needs for a roadmap were identified, existing information were gathered by organisers, to access as much current knowledge and state-of-the-art understanding of the subject as possible. Information was collected from relevant industry reports and previous foresight exercises. In particular, prior roadmapping activities (including the Road to Manufacturing, World Technology Evaluation Center studies, and Roadmap to Additive Manufacturing) were used as important sources of information for the current roadmapping practice (NIST 2013; Bourell et al. 2009).

Step 0b: Defining focus & scope of the roadmap

Findings from previous roadmapping analyses helped refine the focus and scope of the roadmap, highlighting specific factors that require further exploration. As the importance of measurement standards-related issues of metal-based additive manufacturing systems was repetitively highlighted in these analyses, the topic was chosen as the appropriate scope to focus their efforts and best allocate available resources, according to an interviewee.

Step 0c: Designing workshop processes

Designing how the roadmapping workshop is going to be run and executed was then followed. Due to a large number of participants, workshops adopted breakout sessions, where participants were grouped into different topics depending on their experiences and interests. Discussion topics were designed according to the themes that appeared to be important in previous roadmapping exercises, and were used to structure and organise the final roadmap report later. In each breakout session, information was collected and organised through various methods of brainstorming, discussion, and decision-making. A tool called storyboarding – the use of boards and index cards to capture and organise thoughts and ideas to quickly identify priorities and actions – helped facilitate these processes. (NIST 2012)

Step 0d: Selecting participants

Interviewees highlighted the importance of selecting participants representing a balanced view of the industry from various perspectives. 75 experts from various organisations participated in the workshop, though many of them (not dominant) were researchers from industry, research organisations, and academia, as the purpose of roadmapping was to identify research priorities for measurement science (NIST 2013).

Step 0e: Other pre-workshop activities

Other preparatory works were needed before holding workshops, including setting agenda, assigning plenary talks, and preparing handouts for workshop information. In addition, participants were invited to submit 'white papers' prior to the workshop; they were found to be effective for stimulating participants' thinking in advance, and helping organise workshop processes, such as designing discussion topic areas and refining the roadmap's structure (NIST 2013). An organiser of the workshop noted that it was also a useful tool of gathering ideas and insights from experts who could not attend the workshop.

Step 1: Identifying vision and goals

At the beginning of actual roadmapping workshop, future vision and goals were agreed among participants to establish a common sense of direction of the field. These were pre-outlined by organisers based on findings from previous analyses, then presented as keynote presentations during plenary sessions, followed by discussions among participants (NIST 2013). Organisers of the workshop recalled that introductory remarks to set the roadmap's focus on measurement science and metals-based additive manufacturing helped participants focus on specific issues of interest.

Step 2: Appraisal of current status

During plenary sessions, currently available information from pre-collected data were also presented, covering broad landscape of the field, in order to set the stage for a forum to discuss present status of the issue (NIST 2013). Defining key terminology and vocabulary helped articulate current understanding of fundamental concepts, so reducing confusion and ambiguity associated with emerging technologies, according to interviewees.

Step 3: Identifying opportunities and challenges

Significant input was then gathered by participants in each working group to analyse external and internal environments of a particular topic area. The vision and goals of the subject were revisited, to identify detailed needs and objectives of specific areas in terms of technology, process, performance, and capability of additive manufacturing. Based on these objectives as well as information on current status, external factors and internal capabilities were assessed to identify opportunities, challenges, barriers, and gaps associated with achieving the objectives. These identified opportunities and challenges were reviewed, clarified, and voted on the priority according to the order of importance and urgency. (NIST 2013)

Step 4: Generation of strategic options

Viable approaches to solve the identified challenges were then discussed during breakout sessions, drawing on collective experiences and information; existing working groups for each topic area were divided into smaller discussion groups to address each priority challenge (NIST 2013). Detailed action plans for future efforts, along with important milestones, results, pathways, potential stakeholders, and their responsibilities, were generated and prioritised with broad timeframes (NIST 2013). Organisers of the workshop noted that a smaller scope made generation of detailed action plans possible, focusing on particular issues of interest.

Step 5a: Post-analysis and publication

Discussion results of each working group were summarised and briefed-out before concluding the workshop, according to interviewees. It was followed by a post-workshop analysis, ensuring that salient information is packaged in a format suitable for dissemination.

Roadmaps of action plans for priority challenges were also generated (see Figure A.2 in Appendix C for an example). The final reports were then published and distributed in various forms, including hard copies and files on websites, noted an interviewee.

Step 5b: Implementation

Strategies developed through roadmapping exercises were implemented at various levels by different organisations; it influenced the selection, prioritising, and timing of standardisation at relevant committees, and also triggered various activities of both public and private decision makers in furthering capabilities of additive manufacturing and accelerating its widespread use in the industry, according to an interviewee.

Step 6: Review and follow-up

An interviewee noted that once the roadmap was published, participants – and sometimes even non-participants – were given opportunities to review the roadmap for additional input regarding both the contents and process of the roadmapping activities. NIST took responsibilities for maintaining and updating the roadmap on a regular basis, according to another interviewee.

5.2.4 Reflections on the Preliminary Process Model for Standardisation Foresight

A close examination of existing standardisation roadmapping exercises provides insights into how some of the challenges associated with standardisation foresight of modern technologies (see Table 5.1) can be addressed, ensuring that appropriate attention and organisational efforts are paid to issues related to its governance and organisation. Table 5.3 summarises key activities and practices adopted in each case which, by effectively addressing these challenges, provide implications for a more systematic process model for using the standardisation mapping framework.

Preliminary activities of gathering information from previous works as well as participants' initial insights in advance (such as 'white papers' in Case 5) are found to be particularly important for effective design and organisation of foresight analyses. It helps refine the focus and scope of the exercise, by providing syntheses of up-to-date information and additional background of the subject. It also helps identify appropriate stakeholders and supports their

Table 5.3 Case study implications for process model for standardisation foresight

Phases of Road-mapping	**Detailed Steps of Roadmapping**	**Activities and Practices Used in Existing Standardisation Roadmapping Exercises (Cases Illustrating Particular Activities)**	**Proposed Activities for the Process of Using Standardisation Mapping Framework**	**Particular Standardisation Challenges that can be Effectively Addressed by Proposed Activities**
Initiation & Planning	0. Preliminary Activities	- Gather existing information (4,5,6,7) - Identify focus areas (4,5,6) - Decide processes & participants (4,5,6,7) - Gather preliminary insights ('white papers') (5)	- Gather existing information / preliminary insights - Identify scope - Decide processes & participants	- Collation and usage of existing supporting documents - Involvement of and communication between various stakeholders
	1. Vision & Goals	- Identify vision (4,5,6,7,8) - Identify objectives (5,9)	- Identify vision, goals & objectives	- Involvement of a large number of stakeholders with different interests
		- Define major elements (4,6,7,8,9) - Scenario planning (4,8) - Conceptual model (4,6,7,8) - Define essential characteristics (5,6,8)	- Define fundamental concepts (by scenario planning, developing conceptual models, or defining essential characteristics)	- Communication between a large number of stakeholders with different expertise - Coordination and integration of standards activities performed in various disciplines
Input & Analysis	2. Appraisal of Current Status	- Identify current activities (4,5,7,9) - Identify existing standards (6,7,8,9)	- Identify current standards & standardisation activities	- Integration of existing & emerging systems - Integration of standardisation activities
		- Design basic system architectures (6,8)	- Design basic system architectures	- Communication between stakeholders
	3. Identifying Opportunities & Challenges	- Identify current technical / non-technical issues (4,5,6,7,9) - SWOT analysis (4,7)	- Analysis of national / international environments: technical / non-technical issues (e.g. SWOT analysis)	- Participation of a variety of actors from different sectors and disciplines
	4. Generation of Strategic Options	- Identify gaps (4,5,6,8) - Develop use cases (6,7,8)	- Gap analysis (by developing use cases)	- Anticipating standard gaps in emerging technologies with high uncertainties
		- Refine system architectures (6)	- Refine system architectures	- Communication between stakeholders
Synthesis & Output		- Establish strategic priorities (4,5,7) - Develop action plans (4,5,6,7,9) - Cross-review of action plans (4,6)	- Establish priorities based on strategic importance - Develop and review action plans	- Cooperation among various SDOs - All-encompassing approach required for cross-level / cross-domain strategies
	5. Publication & Implementation	- Wider public review process (6,9) - Execute action plans (5,6,7,8) - Provide guidelines for strategies (4,5,7,8,9)	- Review process - Execute action plans - Guidelines for strategic decisions	- Participation and coordination of various organisations
Follow-up	6. Review & Follow-up	- Feedback from participants (4,5) - Modify structure / process (6) - Conformance testing (6)	- Evaluation of strategic analyses process - Conformance testing	

coordinated engagement, by providing bases for establishing common definitions of key terminologies and fundamental concepts in the beginning of foresight exercises; these are critical for efficient communications among participants with different backgrounds and expertise.

Although not shown in illustrative cases presented here, the usefulness of developing system architectures (similarly, conceptual models or reference diagrams) has been clearly demonstrated in other cases, as discussed in Ho (2014) and Ho & O'Sullivan (2016). Developing them at an early stage – even though they are often revised and modified later – particularly helps facilitate discussions and collaborations among participants, by allowing them to have common understanding of structure of complex technological systems. Providing a high-level visual conceptualisation of the overall system, it can also be used in use case analyses, where standardisation gaps are identified to achieve interoperability between different domains and systems composed of different technology bases. Structure and elements of system architectures would differ depending on technologies and systems in question, but Figure A.3 in Appendix C shows a typical example of conceptual reference diagrams used in Case 6 of the smart grid roadmap developed by NIST.

Last but not least, utility-centric methods, such as scenario planning or use case analyses, are important tools adopted in many standardisation roadmapping exercises, as structured ways of anticipating future standardisation needs for highly complex and uncertain technologies. By discussing possible scenarios of how various components and relevant actors would interact with each other, they help identify standardisation requirements that could fulfil these scenarios, while allowing the maximum innovation of the system.

5.2.5 Further Insights from Case Studies to Justify Roadmapping Approach

From the review of existing practices, it is shown that there are increased challenges with strategic management and foresight for standardisation in modern technologies that are becoming more complex, interdisciplinary, and fast-evolving at the same time. Many of these areas have emerged from integration of various domains with different technological bases at different levels, creating a complex system of systems. Such system integration results in new points of contact or interfaces, where standardisation is needed to allow secure interconnections and reliable communications between them. In addition, further challenges arise when existing systems need to be integrated with emerging technologies and systems. They have greater uncertainties in terms of technologies and products, as well as less articulated markets and user requirements, requiring more careful planning and development of standardisation strategies. In order to address such challenges, an all-encompassing approach is needed, allowing cross-level and cross-domain strategy development of standardisation in such complex technological systems. A holistic and systematic approach of roadmapping may be useful, effectively capturing interrelationships and linkages between these various technological domains and systems.

The systems nature of modern technologies also brings about stakeholder complexities associated with strategic foresight for standardisation. A large number of stakeholders representing various perspectives need to be engaged, including the industry (e.g., companies and trade associations), research laboratories, academia, government, and SDOs. This requires communications between participants with different expertise and perspectives, as well as collaboration and coordination of activities performed by various innovation actors. Gathering various stakeholders with different perspectives and bringing consensus among them, the roadmapping approach is suggested to be adequate and useful for addressing such issues with standardisation foresight in modern technologies. Many interviewees agreed that such roadmapping exercises not only provide a more comprehensive and systematic overview of complex systems of standardisation, but also become important forums for discussions where participants share and exchange their knowledge. This leads to collaborative innovation activities among stakeholders from various organisations and disciplines, thus facilitating knowledge diffusion and development across the whole innovation system.

In addition, due to the increased complexity and systems nature, standardisation roadmaps are generally based on other supporting documents with previously analysed information, that need to be collated and incorporated into current foresight exercises. As the preliminary process model (shown in Figure 5.1) is essentially based on the general roadmapping process which is flexible and adaptable, it is also expected to be readily adaptable within previously developed foresight analyses, ensuring that existing information are effectively incorporated in the current exercise. Although it may not be entirely sufficient to be applied for standardisation foresight of complex technological systems, studies of existing roadmapping exercises provide useful insights and implications for how such foresight processes can be structured, managed, and governed, making the most use of information available. These processes are discussed in the next section, particularly highlighting how relevant information from previous analyses are incorporated in current foresight exercises, helping manage complexities involved in standardisation of heterogeneous technological systems more effectively.

5.3 Development of Process Model for Standardisation Foresight

5.3.1 Process Model for Standardisation Foresight (Ver.1)

Based on lessons learnt from case studies as well as additional review of literature informed by them, a more systematic and structured process model for using the standardisation mapping framework is developed, to effectively address some challenges related to strategic foresight for standardisation in modern technologies (see Figure 5.4). Incorporating useful steps and activities adopted in actual standardisation roadmapping practices, the proposed process helps ensure that appropriate levels of additional care, systematic attention, and organisational efforts are paid to issues such as governance, stakeholder inputs, and system

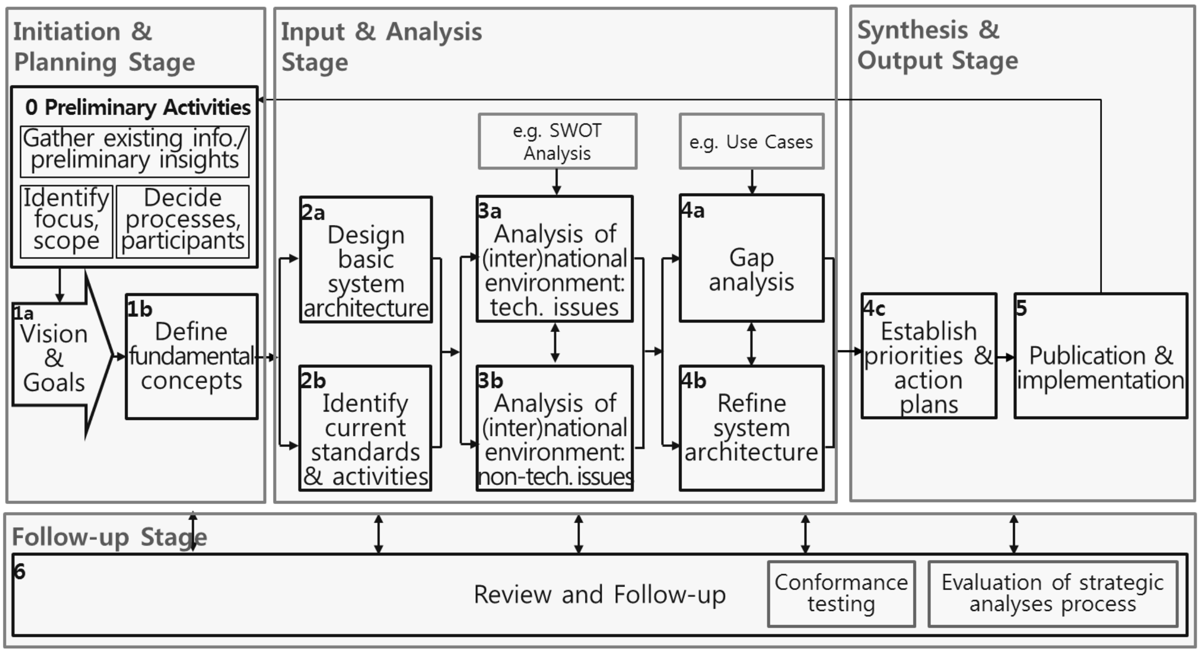


Figure 5.4 Process model for using the framework for standardisation foresight (ver.1)

characterisations. The actual process would be more complex, dynamic, and iterative in nature, but it is still helpful to begin with a structured and rational view based on systems and process thinking (Phaal et al. 2010). A step-by-step description of the process model is presented, with illustrative examples from case studies.

Step 0: Preliminary activities

It is repeatedly highlighted in case studies as well as academic literature (e.g., Morell & Steward 1995) that preliminary activities during the planning and initiation phase are important first steps, for both the success of foresight exercises and effective standardisation. First, existing information is gathered from previously generated reports and other foresight analyses on relevant issues, to access as much current knowledge and state-of-the-art understanding of the technology and its standardisation landscape as possible. Current foresight analyses can even be built on previously published documents, as in Case 6, Case 7, and Case 8 (NIST 2010; Hogan et al. 2011; NPE 2012). As they are often syntheses of collective experiences and up-to-date knowledge representing various perspectives, using this information can significantly enhance efficiency of the foresight process and quality of outputs. Additional background information may also be collected by inviting participants, once identified, to submit initial documents such as 'white papers', as observed in Case 5.

Based on existing information gathered, the focus of analysis needs to be defined to help clarify its scope and boundaries, which are critical for the success of foresight activities as well as standardisation projects (Sherif et al. 2005). Processes of how the foresight analysis is actually going to be run and executed are also decided. Workshops with breakout sessions can be employed to foster collaborations and interactions among various stakeholders; discussion topics in each breakout session can be designed according to important themes identified from previous analyses, as adopted in Case 5, Case 6, and Case 7.

Selecting participants is another essential step, as the output of foresight activities heavily relies on the knowledge and insights they bring into the process. In addition, the range of stakeholders and experts to be integrated in standardisation foresight analyses is often wider and more complex than technology foresights, because of the significant impact of standardisation on wider society (European Commission 2011; Goluchowicz & Blind 2011). However, often insufficient efforts are paid to the identification of an appropriate mix of stakeholders and their involvement in standardisation, simply due to the lack of awareness of this issue (de Vries et al. 2003). Importance of this step is further discussed in section 5.3.2.

Step 1a: Identify visions and goals

When the actual workshop for future-oriented analyses begins, a future vision of the field and its broad goals in terms of standardisation need to be shared and agreed among participants, in order to establish a common sense of direction which is critical for the success of strategic standardisation. Although it is difficult to achieve consensus in the beginning on definite goals of standardisation in such complex systems, it is necessary to define an initial high-level vision to develop common strategies (Emerging Industries Section 2001; Phaal et al. 2010). Articulating objectives and expected outcomes of foresight activities may also help guide the general direction of analyses.

Step 1b: Define fundamental concepts

Standardisation involves participation of a variety of stakeholders with different backgrounds and expertise, leading to increased communication challenges; additional confusions and ambiguities may also exist due to new terminologies and vocabularies relevant to emerging technologies. Common definitions of fundamental concepts relevant to the technological system under consideration thus need to be defined, to reduce uncertainties and to facilitate communications among participants during exercises, so supporting 'legitimation' and 'creation and transfer of new knowledge' functions of standardisation in innovation systems (see sections 2.2.3 and 2.2.6).

Due to the systems nature of modern technologies involving considerable information exchange, defining major elements of systems – such as main components, domains, actors, and service models – can play important roles in providing better understanding of the system (NIST 2010; Hogan et al. 2011; NPE 2012; TTA 2013). Sometimes, tools such as scenario planning and conceptual models, as adopted in Case 4 and Case 8, may facilitate this process, by allowing a clearer overview of the system (Hogan et al. 2011; TTA 2013). However, care needs to be taken, as the lack of structured methods in developing and evaluating scenarios may result in complexities due to an unhelpfully wide variety of different types – in terms of forms and contents – of scenarios, as criticised by some interviewees. For domains involving integration of existing and emerging systems, it may be more efficient to first define the existing system landscape coherently and completely, before defining the additional level of integration and its emergent behaviour (DKE 2014).

Step 2a: Design basic system architectures

"An architecture models the structure of a system and describes the entities and interactions within the system (NIST 2010, p.28)." Designing basic system architectures allows systematic analyses of interrelationships between different technologies, and also supports communications between various stakeholders with different expertise, so facilitating cross-domain strategic standardisation as in Case 6 and Case 8 (NIST 2010; Hogan et al. 2011). Allowing efficient dissemination of technical information and forming a baseline from which new technologies and innovations emerge, basic system architectures can thus enhance the 'creation and transfer of new knowledge' function of standardisation in innovation systems (see section 2.2.6). It may not be practical to develop a definite, single, and all-encompassing architecture from the beginning for a complex system of systems, such as smart grid and smart manufacturing; independent, yet interconnected architectures for subsystems can be developed instead, then continuously revised as the technology evolves over time and as a higher level of consensus is reached throughout foresight analyses (NIST 2010).

Step 2b: Identify current standards and standardisation activities

Once basic system architectures are defined, they can be used as "conceptual reference model(s) for discussing the characteristics, uses, behaviour, and other elements of… (the system) and the relationships among these elements (NIST 2010, p.28)." Current status of standards and standardisation activities relevant to the system under consideration can thus be discussed and organised with reference to system architectures, as adopted in most cases (NIST 2010; NPE 2012; DKE 2014). Since many recent technologies emerge from the integration of previous generation technologies with varieties of ICT, existing standards may be originally developed in support of pre-exiting, analogous technologies; for example, some of the existing standards relevant to cloud computing are originally designed for web services and the Internet (Hogan et al. 2011). Hence, relevant standards and standardisation activities can be identified by examining the standardisation landscape of existing, related technologies.

Step 3: Analysis of national / international environments: technical / non-technical issues

Then, national and international environments need to be analysed to identify opportunities and challenges in terms of standardisation; structured tools such as SWOT analysis can be helpful, as used in Case 4 (TTA 2013). During the analysis, it is critical to consider various aspects other than just technological issues, as effective standardisation requires strong linkages and coordinated management among various activities, particularly between the technical work of standardisation and market development for standards-conformant products (Morell & Steward 1995). Many interviewees highlighted the importance of ensuring well-balanced representations of various perspectives, including technology, market, industry, regulations, and government policies; increasing attention is paid to intellectual properties, such as patents, as well. In discussing their standardisation foresight methodology developed for DIN, Goluchowicz & Blind (2011) also highlight the importance of considering various indicators, including technological change, global markets, governance, and society and innovation, in order to systematically identify standardisation topics.

It is important to analyse these issues not only within particular technological domain under consideration, but also in other related domains or markets, as they may also have significant influences in modern technologies with the interdisciplinary and convergent nature. An interviewee in Case 4 gave an example of standardisation of Digital Multimedia Broadcasting – i.e., a digital radio transmission technology for sending multimedia such as TV, radio, and other data to mobile devices – which failed due to the lack of consideration of trends in other mobile technologies. As similar services can now be provided using smart phones, the technology became obsolete, despite significant efforts put into developing relevant standards. In order to reduce such risks, it is important to analyse various issues in other relevant areas from a more systematic perspective; analyses of crosscutting areas where different disciplines meet each other (as in Case 4 and Case 5) may be useful.

It is to be noted that such analyses are particularly important for standardisation foresights whose goal is to secure national competitiveness of the industry in international markets (NPE 2012; TTA 2013; DKE 2014).

Step 4a: Gap analysis

In order to address challenges and opportunities identified in the previous step, a gap analysis needs to be performed, identifying key areas where standardisation is needed to support the innovation system. A structured method of use cases (adopted in Cases 6 through 8) can be a useful tool for anticipating future directions of technologies and relevant standardisation needs. Describing how systems would interact from a utility-centric perspective with the aid of system architectures, use cases help determine standardisation requirements to achieve interoperability within various parts of the system (NIST 2010; Hogan et al. 2011; NPE 2012;

DKE 2014). These requirements are then compared against the list of existing standards or current standardisation activities identified in Step 2b, in order to identify gaps that need to be closed in the future. Being descriptive rather than prescriptive, use case methods allow maximum innovation in emerging areas with high uncertainties, yet ensure their ready deployment and interoperability within the system (NIST 2010); they thus reinforce the 'creation and transfer of new knowledge' function of standardisation in innovation systems (see section 2.2.6).

Step 4b: Refine system architecture

Gap analysis from use cases may also reveal any gaps in the architectural principles and concepts that have not been aware earlier, noted an interviewee from Case 6. Hence, the basic, simpler version of system architectures designed in Step 2a can be refined, by incorporating additional requirements identified through use case analyses; providing a common framework of reference, refined architectures can be used to describe, discuss, and develop strategic action plans for standardisation.

Step 4c: Establish priorities and action plans

Standardisation gaps identified through use case analyses are then assessed in terms of various factors – e.g., their strategic importance, urgency, and estimated timeframe – in order to prioritise and develop action plans to address them. Strategic options and detailed plans for each action are then generated, including whether to develop new standards or revise existing standards, identifying which SDOs should be responsible, and detailed timelines for each task. Depending on positions of the national industry in international markets, strategic choices between leadership and followership can be made; leaders identify and participate in major SDOs, whereas followers need to monitor the results of rulemaking processes or to learn how to meet the requirements of the rules (Choi 2013). As standards are open documents for all, strategic decisions of whether to standardise and share with competitors (open, so-called 'white-box' strategy), or to privatise and keep it proprietary (closed, so-called 'black-box' strategy) may also be necessary (Grindley 1995; Choi 2013). Interviewees from Case 4 and Case 6 noted the importance of reviewing strategic action plans across related domains and systems, in order to ensure consistency and effectiveness of strategies developed. Due to the systematic and interdisciplinary nature of modern technologies, comprehensive reviews of interrelationships and linkages between different domains and their standardisation activities are critical to support overall innovation systems more effectively.

Step 5: Publication and implementation

A draft version of the output of foresight analyses may go through a public review process, engaging wider stakeholders who did not have opportunities to participate in workshops (as in Case 5, Case 6, and Case 9). Reviewed strategic actions may then be implemented by relevant organisations and committees, influencing the selection, prioritising, and timing of standardisation activities. According to multiple interviewees, they can also trigger various activities led by both public and private decision makers in supporting their innovation systems. In addition, as syntheses of up-to-date knowledge, they may be used as critical sources of information for subsequent foresight analyses in relevant fields (thus indicated as an iterative loop in Figure 5.4). For example, contents of the German Standardisation Roadmap for Electromobility in Case 7 are incorporated in a similar roadmap developed by the Transatlantic Economic Council (NPE 2012), while contents of the Cloud Computing Standards Roadmap in Case 8 are incorporated into a wider Cloud Computing Technology Roadmap (Hogan et al. 2011; Badger et al. 2011).

Step 6: Review and follow-up

As foresight activities such as roadmapping are ongoing learning processes rather than a single, one-off activity, it is important to continuously review and revise its development process through evaluation and learning, in order to support the ongoing knowledge management. Feedback from participants is critical to improve the overall foresight processes, so surveys or questionnaires may be employed, as observed in Case 4. Based on these feedbacks as well as learning from experiences, processes and relevant governance structures of foresight exercises can be modified where necessary, as observed from Case 6. A number of interviewees from Case 6 emphasised that conformance testing of developed standards is also an important step of review processes, as they are often incomplete, or even complete standards may be interpreted differently by different stakeholders. The importance of conformance testing is also discussed in various literature (e.g., Lehr 1995).

5.3.2 Implications Regarding Participants

Most interviewees highlighted the importance of participants in standardisation foresight, as the reliability and validity of its output heavily relies on their knowledge and insights, as also discussed in exiting literature (e.g., Goluchowicz & Blind 2011). In addition, case studies showed that stakeholders from different types of organisations have different perspectives, thus making different contributions. According to multiple interviewees, participants from the industry – including manufacturers, service providers, and utilities – provide substantial knowledge and resources on real market needs and actual functioning of systems, as they are at the cutting edge of the industry with better understanding of markets and systems. On the other hand, participants from research organisations provide more state-of-the-art knowledge of science and technology at research stages, whereas participants from academia tend to offer longer-term views that other participants may not yet be aware of. Hence, selecting an appropriate mix of participants with complementary perspectives is considered critically important to ensure a balance of contributions.

The lack of such balance in stakeholder representation may lead to standardisation activities that guide innovation systems in an inappropriate direction. Interviewees from Korea expressed their concerns that strategy maps that are mainly developed by researchers with purely technical perspectives may overly generate research-oriented standardisation gaps which do not address real needs of the industry. On the other hand, interviewees from the US identified potential dangers of dominant participation from the industry in focusing on short-term benefits only, as their main objective is to create economic value through business models. Such unbalance in participants is also identified by existing literature as a critical barrier, limiting overall perspectives of standardisation in innovation systems (Morell & Steward 1995; de Vries et al. 2003); the lack of participation from user groups (Jakobs et al. 2011) and small companies (European Commission 2011) is particularly highlighted. A well-balanced participation of stakeholders representing various perspectives – including those of researchers, private companies of all sizes, economists, market analysts, regulators, and users – is thus essential, for effective foresight analyses of standardisation in support of innovation.

5.3.3 Implications Regarding Potential Roles of Government

Among various roles of government in standardisation (as discussed in section 4.4.1.2), needs for its active engagement as convenor or coordinator of strategic foresight analyses are highlighted in case studies, due to the participation of various stakeholders with different perspectives. Many interviewees noted that government can facilitate collaboration of a variety of innovation actors by helping them coordinate and align their activities in a more systematic way, supporting the effectiveness and efficiency of the overall innovation system. The mediating role of government may also include helping gain legitimacy and social acceptance by resolving conflicts between various stakeholders or innovation systems, which are critical functions of standardisation in innovation systems, as discussed in section 2.2.3.

Such convening and coordinating role of government in standardisation is becoming increasingly important with the growth of complex technological systems, according to multiple interviewees. Their complex and heterogeneous nature requires various stakeholders with different backgrounds and interests to work together, resulting in additional challenges in communication and cross-sectoral cooperation. Various SDOs with different expertise also need to work together, requiring coordination of their activities and harmonisation of standards developed by them. However, they often compete for standardisation, as sales from standards account for substantial amount (e.g., 80% in the case of ASTM) of their income (OTA 1992). In addition, interviewees noted that there are generally multiple federal departments and agencies involved in supporting such interdisciplinary technological systems, whose activities and interests also need to be coordinated. Therefore, there are increasing roles for government to help convene such a wide variety of actors and to align their standardisation efforts, addressing challenges with complex innovation system.

Even when such convening and coordinating role can be conducted by other organisations (e.g., non-profit industry consortia as in Case 4), government may still play active roles by enabling or funding standardisation foresight activities, especially in areas of national economic or societal importance. ICT convergence in Korea, cloud computing in the US, and smart manufacturing in Germany are all considered to be areas of strategic importance for national economic competitiveness; whereas smart grid and electromobility standards serve as critical public resources required for effective operations of national infrastructures. In order to avoid public good problems (discussed in section 2.4.1), government needs to play a more active role in supporting relevant standardisation and its strategic foresight. Blind (2013, p.26) also emphasises such roles of government by saying that "public policy should propose the initiation of standardisation, especially in those areas of high relevance for society, when industry is reluctant to start because of missing commercial perspectives." These are suggested to be particularly critical in ICT-enabled complex systems (such as smart grid), where standardisation is essential to ensure compatibility and interoperability of systems.

5.3.4 Other Challenges and Issues to be Explored

It appears from the case studies that different strategic approaches to standardisation foresight were adopted by leaders and followers of technology and standardisation, reflecting contextual variations in terms of both technological capabilities and history of standardisation systems. As a latecomer country with a lack of resources but a number of leading technologies in certain areas, Korea adopted a more targeted approach in developing short-term roadmaps to examine their strategic positions in international standardisation for particular sectors of established systems. On the other hand, as experienced leaders in both technology and standardisation, Germany and the US took a broader and more holistic approach in developing longer-term roadmaps to anticipate challenges and issues with future standardisation needs in overall systems; they thus use more anticipatory and structured tools, such as system architectures and use case analyses, to address higher risks and uncertainties associated with complex, emerging technologies. Such difference in approaches due to different purposes of strategic foresight analyses also results in different roles of government and types of stakeholders participating in roadmapping exercises. It is an early observation with only small number of cases, hence more comparative studies are needed to explore such issues in the future.

5.4 Concluding Remarks

A systematic and structured process model for using the standardisation mapping framework (developed in Chapter 4) for standardisation foresight is developed, based on literature review and lessons learnt from case studies of existing standardisation roadmapping exercises in various contexts. It follows four major stages of a general strategic roadmapping process: initiation and planning, input and analysis, synthesis and output, and follow-up. As both standardisation and foresight analyses require large amount of information from a variety of stakeholders, preliminary activities to gather existing information and additional insights from participants are found to be useful for increasing the efficiency and quality of analyses. Particular tools that appeared to be effective in existing practices, such as system architecture and use case methods, are also incorporated, to effectively address challenges due to complexities and uncertainties associated with standardisation of modern technologies that are interdisciplinary and systematic in nature. In addition, case studies provide useful implications regarding different roles and contributions made by various stakeholders, as well as potential roles of government in standardisation and relevant foresight activities. The next chapter will discuss the effectiveness and completeness of the proposed process model and the framework (developed in Chapter 4) using an in-depth case study, leading to their further development and refinement.

6. REFINEMENT OF FRAMEWORK AND PROCESS MODEL

In this chapter*, the standardisation mapping framework and the process model for using it (proposed in Chapters 4 and 5, respectively) are further developed and refined, using an in-depth, longitudinal case study. History of PV innovation and relevant standardisation activities over an extended period of time is analysed, in order to verify, and also provide greater detail and clarities of, elements and features incorporated the framework and process model. The overview of the case study is first presented along with empirical context of PV technology, followed by detailed description of methods used in the study. Exploring how standardisation supports innovation throughout the history of PV technology, the case study illustrates features of the current framework and process model, and also justifies the use of the roadmapping approach to address challenges in systematic and future-oriented analyses of standardisation. In addition, it explores additional trends and patterns into complex and dynamic interplays between standardisation and innovation, providing greater understanding of their dynamics. This chapter concludes with the revised framework and process model, followed by discussions on remaining challenges and issues with standardisation as identified from the case study.

6.1 Overview of the Case Study

6.1.1 Empirical Context of PV Technology

The case of PV technology is selected, because of its technical complexities and variations,

* Part of the research contained within this chapter has been peer-reviewed for the EURAS 2016 conference, and invited for publication in an international journal. However, this offer has been declined, as it is currently being revised for resubmission to another journal.

including various application areas, a high level of systems complexity, and a variety of technology types, all of which add intricacy and variety to its standardisation activities, providing rich historical information for this study. Initially developed for niche applications for specialist user groups in space and telecommunication sectors, PV has made an interesting transition to residential and utility applications for non-specialist consumers, as the result of a series of socio-environmental issues such as oil crisis and climate change (Hill 1992). There are also various levels of systems complexity involved in PV throughout its development, including solar radiation, cells and modules, PV systems, and Balance of System (BOS, i.e., electronics and other components, such as batteries and power controllers, that allow proper functioning of PV systems) (Perlin 2002). In addition, there are a number of different types of PV technology, depending on types of cells, such as crystalline, thin-film, and organic, as well as depending on types of modules, such as non-concentrating and concentrating modules (Perlin 2002). These all provide rich information to explore various issues associated with complex and dynamic interplays between standardisation and innovation over an extended period of time.

In addition to the technology-based nature of innovation, its socio-economic aspects throughout the history of PV also make it an interesting case study. Due to the importance and urgency to address social and environmental challenges such as climate change and energy security, policymakers have been motivated to promote the fast deployment of PV technology. Various regulations and supporting programmes have thus been introduced across the world, resulting in dramatic technological and industrial development of global PV industry (Hill 1992). In particular, the current study starts exploring standardisation in the innovation context of the US, as it dominated early PV standardisation. As the birthplace of PV technology, most of early innovation and development activities of PV (since its discovery) took place in the US; PV standards developed by organisations based in the US thus had significant influences in international standardisation activities. As international perspectives became increasingly important in standardisation with the development of global PV markets, the study later expands its scope to international contexts as well.

6.1.2 Case Study Methods

Given retrospective nature of the research, over 200 documents from various sources – such as standard publications, industry trade magazines, official reports published by governments and research laboratories, conference proceedings, and journal papers – have been collected, representing various perspectives of innovation including technology (e.g., Perlin 2002; Lynn 2010), industry (e.g., Colatat et al. 2009; Lamont 2012), and policy (e.g., Hill 1992; Laird 2001). Although many of these documents were available in the public domain, key documents and insights were also obtained from the National Renewable Energy Laboratory (NREL) library, which houses extensive resources related to the history of PV technology that are not accessible elsewhere. These documentary data, as well as the rich description offered in PV industrial roadmaps developed by Friligos (2010), were used to identify key events and activities during the historical development and standardisation of PV technology.

Using the *Expert Scan* method discussed in section 3.5.1, semi-structured interviews were also carried out with experts who have been involved in various standardisation activities related to PV. Interviews not only complemented documental resources by providing contextual backgrounds and details, but also generated insights into relationships and linkages between key events and activities, particularly regarding how standardisation supported innovation activities of PV. Collected documents, as well as preliminary studies – both quantitatively and qualitatively – on PV standardisation (Ho & O'Sullivan 2013; Ho & O'Sullivan 2015), have been drawn upon to develop a pre-populated map (i.e., preliminary version of Figure 6.1) and design interview protocols (see Appendix B).

Interviewees were initially contacted from the list of members in TCs specifically for PV in major standards organisations (ASTM E44, IEC TC82, IEEE SCC21, and PV Committee in SEMI), then approached using "snowball sampling" (Goodman 1961). A total of forty-two experts, selected from a variety of organisations – including national laboratories (fourteen), private companies (thirteen), independent consultants (six), academia (four), governments (three), and standards organisations (two) – across various areas of PV technology, participated in interviews, ensuring the representation of varied perspectives; see Table A.3 in Appendix A for detailed profiles of interviewees. It is to be noted that although most of them are from the US, key interviewees also had strong understanding of international perspectives of PV standardisation – such as major activities across the world and their implications to standards – based on their experiences in international standardisation committees.

6.2 Case Study Analyses

6.2.1 Historical Analyses of Innovation and Standardisation of PV Technology

Based on collected data, detailed descriptions for the history of innovation and standardisation of PV technology are presented in a narrative style. Structured in chronological order, the narrative is also captured and visualised on the standardisation mapping framework developed in Chapter 4 (see Figure 6.1 for summary, and Figures 6.2 through 6.5 for details), using conventions that are previously introduced (i.e., standards are coded by letters indicating their roles and functions, followed by numbers indicating the order of appearance). Using both frameworks and narratives, the following sections present detailed illustrations of how key standards, which are identified by interviewees to have played significant roles throughout the innovation journey of PV technology, interacted with other innovation activities. These can be organised into four broad phases of innovation, divided according to the evolution of their main application areas: (i) transition from space applications to terrestrial applications, (ii) demonstration of grid-connected applications, (iii) introduction of large power systems, and (iv) emergence of smart grid. It is to be noted that only key standardisation and relevant innovation activities are shown and discussed here due to space constraints; thus gaps in the roadmap do not mean that there were no innovation or standardisation activities, but they were less significant in PV history.

6.2.1.1 Transition from space applications to terrestrial applications (1976~1985)

Although electricity generated from the PV effect was first observed in 1954, it was not until the oil crisis in the 1970s that PV gained great attention as an alternative source of energy, due to its high risks (Ksenya 2011). To address the problem of energy security, various government programs and legislations were proposed to support research on PV for terrestrial applications, and needs for appropriate standardisation were identified among the growing number of stakeholders involved in PV research (Ross & Smokler 1986). Consequently, two PV Measurement Workshops were organised, resulting in the technical report (NASA TM 73702) which presented the first set of consensus-based standards (NASA 1977). Although nearly sixty people participated in workshops, an interviewee noted that a large number of participants were researchers from government laboratories, as they were more experienced in this emerging technology with a niche market of space applications.

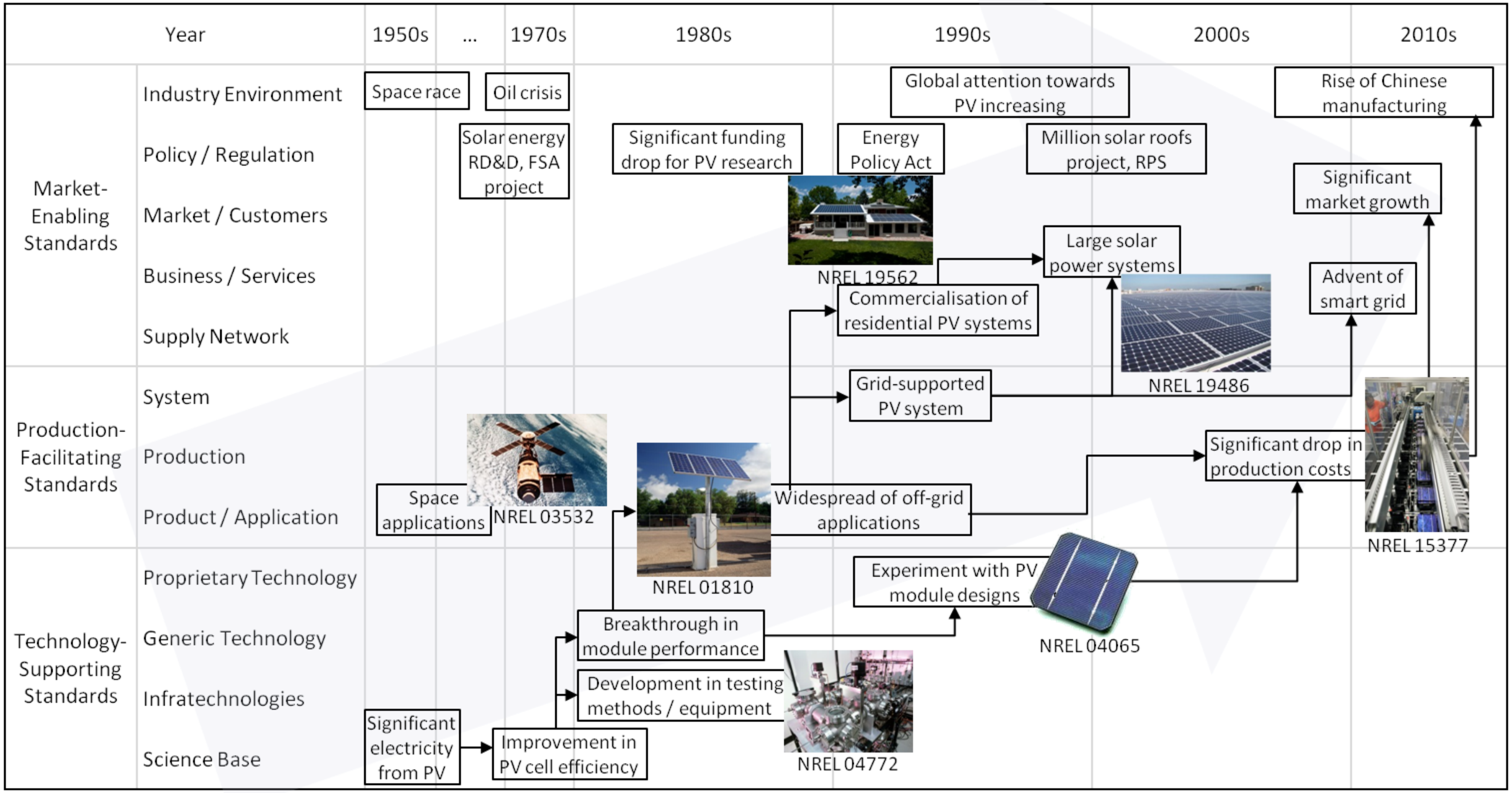


Figure 6.1 Historical analyses of innovation and standardisation of PV technology (all images from NREL Image Gallery (NREL 2016))

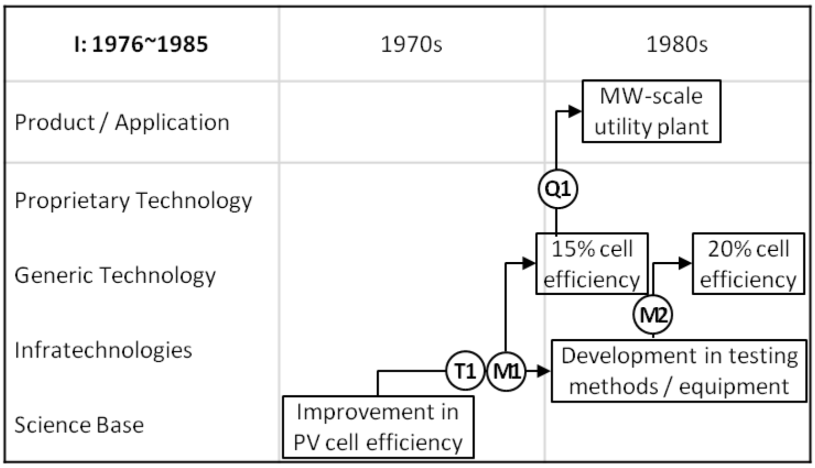


Figure 6.2 Innovation and standardisation of PV technology from 1976 to 1985

T1: Terminology standard for PV technology

One of the most significant information incorporated in the report (NASA TM 73702) was the definition of key terminologies, including cells, modules, arrays, and efficiency (NASA 1977). According to multiple interviewees, it made the PV community agree on what language they use, removing any potential confusion and facilitating communications when writing standards or using them for research.

M1: Measurement / testing standards for PV cells and modules

The report also presented reference spectrum, standard test conditions, equipment, and procedures to be used in testing and measurement of cell performances (NASA 1977). Interviewees noted that performance measurements of PV had many problems prior to its publication, as multiple groups would use their own methods of measuring cell efficiencies with respect to different solar spectrum, making it difficult to compare their research results. Having a standard method of measurement made it easier to compare performances of cells developed by different researchers, and also assess the current status of technology development through rigorous traceability, noted multiple interviewees. An interviewee added that accurate assessments of research deliverables were particularly valuable for program managers and government agencies to make funding decisions, guiding research directions for technology improvement. Therefore, by increasing accuracy and efficiency of PV research, terminology and measurement standards facilitated the development of both PV cells and technical infrastructure required to support PV development (including measurement methods and standard databases).

Q1: Qualification testing specifications for PV modules

Despite the significant improvement of generic PV technology in late 1970s, widely used terrestrial applications did not exist due to the lack of reliable PV modules; many interviewees noted that customers (such as government and installation companies) were reluctant to install them, as early modules developed in late 1970s and early 1980s frequently failed in the field due to their low quality and reliability. Hence, Jet Propulsion Laboratory (JPL) initiated a project to foster cooperative efforts between researchers and industry, in order to stimulate the development of PV applications (Ross & Smokler 1986). Requiring manufacturers to pass a set of prescribed tests to qualify for block procurements of PV modules, the project greatly increased the quality and safety of modules in the US market (Colatat et al. 2009). The last block procurement in 1981, *Block V*, was particularly remarkable, with its specifications document becoming the de facto standard for module quality (Osterwald & McMahon 2009). Specifying both test procedures and performance criteria to pass the tests, it helped designers and manufacturers to develop high-quality products, and also ensured customers to have confidence in modules, leading to the widespread of off-grid terrestrial applications, according to multiple interviewees. For example, the first large, megawatt-scale PV utility plant was built by Sacramento Municipal Utility District in 1983 (Yerkes 2004).

M2: Refined measurement / testing standards for PV modules

Despite increasing research activities in private sectors to meet growing market needs for terrestrial PV applications, reference model and detailed measuring procedures developed by NASA were not publicly available, hampering effective performance of R&D and diffusion of its results in a wider group of researchers, noted an interviewee. Needs for more refined and publicly available standards were thus identified by the industry, leading to the establishment of TCs specifically dedicated to PV in ASTM, IEEE, and UL (Ross & Smokler 1986). According to interviewees, an ANSI Steering Committee on Solar Energy was established for coordination and avoidance of duplicative efforts in standardisation among these SSOs. Their works were thus divided according to the expertise and nature of organisations: ASTM focusing on testing of cells and modules, while IEEE being responsible for standardisation related to PV systems.

Based on their expertise in test methods and specifications, ASTM E44 – mainly consisted of researchers at the time – developed a number of PV measurement and testing standards. Published in 1982, ASTM E891 and ASTM E892 – presenting terrestrial solar spectral irradiance tables with more refined data and strong technical basis – allowed anyone to generate the same reference spectrum across the world, making sure that their research results are verifiable and comparable, according to multiple interviewees. Interviewees also highlighted that by documenting detailed and clarified test conditions and procedures of measuring cell efficiency, ASTM E948 allowed more accurate and consistent measurement of performances. In addition, a series of standard methods for calibration and characterisation of reference cells (e.g., ASTM E1039 and ASTM E1362) were published in late 1980s, ensuring accuracy, stability, and reliability of efficiency results, noted another interviewee.

Although these ASTM standards were solution-describing standards outlining procedures without setting criteria (unlike JPL specifications), they also facilitated research activities of generic PV technology, by providing a level playing field and guiding research directions for more effective technology improvement, claimed an interviewee. Moreover, they led to the development of measurement techniques and testing equipment, which were important infratechnologies themselves; thus allowing enhanced traceability, significant improvements in cell performances could be achieved in 1980s, despite the decreased public research funding in favour of nuclear energy over PV (Jones & Bouamane 2012). Because of their highly scientific and research-intensive characteristics, researchers from laboratories such as NREL actively participated in the development of these standards, by providing invaluable resources and experiences in testing PV cells and modules (McConnell 2006).

6.2.1.2 Demonstration of grid-connected applications (1986~1995)

The significantly improved quality of PV modules, along with the increasing attention due to the climate change in late 1980s, led to the growth of PV production and market. Yet, this was limited to standalone, off-grid PV applications, as utility companies were still concerned about safety and reliability of this new technology being connected to their grid, according to multiple interviewees.

C1: Compatibility / interface standard for residential PV systems

Compatibility and interface standards which describe interface construction techniques and operating procedures for connecting PV systems with the utility was thus needed, in order to

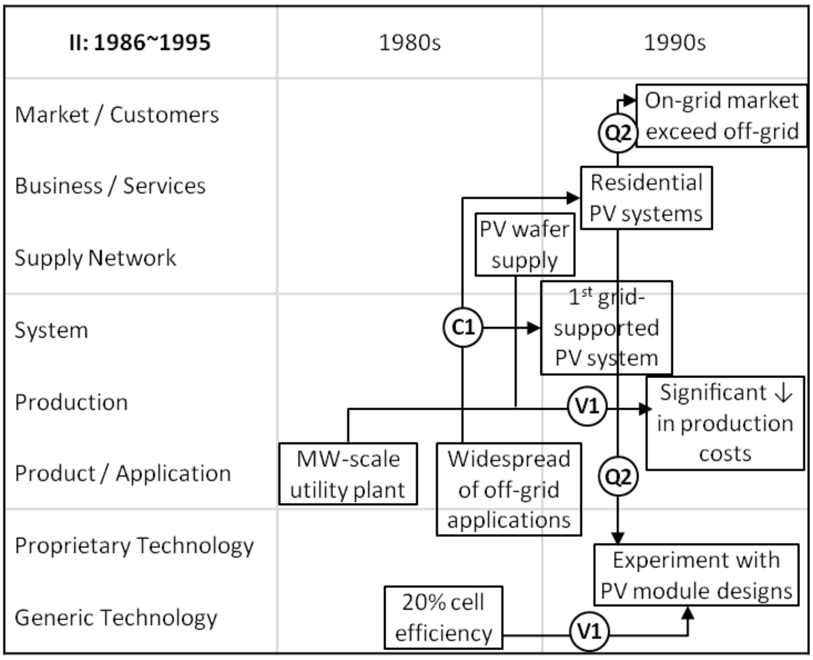


Figure 6.3 Innovation and standardisation of PV technology from 1986 to 1995

give confidence to utility companies, noted multiple interviewees. With their expertise in electrical and electronics systems, IEEE SCC21 (Standards Coordinating Committee on fuel cells, PV, dispersed generation, and energy storage) developed IEEE 929 in 1988, documenting recommended practice for utility interface of residential and intermediate PV systems (Hester 2000). Prior to its development, PV applications had been treated as other large-scale power generators, creating unnecessary barriers to its wide deployment in the market, according to interviewees; hence, this anticipatory standard was a prerequisite for integration of PV systems in larger grid systems, leading to the commercialisation of on-grid, residential solar power systems in early 1990s.

V1: Variety-reduction standard for wafer size

An interviewee with long experience in the PV industry recalled that until 1980s, manufacturers often used wafers designed for computer chip manufacturing, as these were readily available from the large industry of semiconductor at the time. With demonstration of the potential for grid-connected systems and increased government supports in late 1980s, the PV market of significant size had been established, and manufacturers started experimenting with the wafer specifically designed for PV modules (Räuber 2003). By early 1990s, 125mm wafer – by Siemens and Sharp – appeared as the dominant design generating high outputs with low production costs, noted the interviewee. This responsive, de facto standard based on proprietary design allowed more economic production of PV modules and applications by generating economies of scale (for both wafer suppliers and manufacturers), leading to the significant drop in production costs, according to multiple interviewees. Another interviewee from research laboratories noted that the standardised wafer size also increased R&D efficiency by facilitating communications between researchers and product designers.

Q2: International qualification standard for PV modules

Due to the growth of PV production and market, along with global attention towards PV, demands for internationally accepted quality standards arose by manufacturers so that they could sell their products worldwide, noted multiple interviewees. Hence, IEC 61215 was developed in 1993, defining specific sequences, conditions, and requirements for the design qualification of PV modules (Arndt & Puto 2010). As a participatory standard under the evolutionary process with improvements incorporated as experience is accumulated (Treble 1986), this quality standard presented more refined and advanced testing methods by incorporating other national or regional standards that already existed, including those developed by JPL and the European Commission's Joint Research Centre; it thus led to the wider adoption and deployment of PV products and systems (Ossenbrink et al. 2012). In addition, interviewees highlighted that it facilitated manufacturers' experiments with PV module designs, trying to identify low-cost designs that still pass the tests. While existing manufacturers could use the standard for such gradual improvement of PV modules, new entrants could also use them to identify and solve problems before market introduction, thus increasing the efficiency of product development processes (McConnell 2006). It is also to be noted that as the PV industry grew and more manufacturers entered into the market, companies also became more involved in the development of quality standards to gain competitive advantages through standardisation, according to multiple interviewees.

6.2.1.3 Introduction of large, complex power systems (1996~2005)

With the increasing global awareness towards renewable energy as shown by strong government supports in Germany and enactment of Kyoto Protocol, US governments initiated a number of programs – including Million Solar Roofs Project and Renewable Portfolio Standard – to increase the PV market in late 1990s (Räuber 2003; Colatat et al. 2009). Although this led to the development of more reliable and cost effective PV systems, the widespread of large PV applications and power systems could not be achieved without relevant standards in place.

Q3: Quality / reliability standard for Balance of Systems (BOS)

In addition to the quality of PV modules, the quality of other electronic components required – such as inverters, batteries, and power controllers, all of which are called BOS – also had to be ensured, in order to increase confidence for users (such as investors, installers, and project developers) of PV systems. UL 1741, the standard for inverters, converters, and controllers for use in independent power systems, was thus developed in 1999, based on IEEE 929 with addition of reliability and safety issues (Zgonena 2011). It was also developed through a close coordination with the task group for National Electrical Code (NEC) Article 690 – which is an industry supported group addressing the safety for installation of PV systems – to ensure more effective and harmonised standardisation among different organisations (Bower 1997). A number of interviewees agreed that this national standard resulted in the wide adoption of on-grid PV applications and systems in the US, by increasing reliability and consumer confidence for larger PV systems. Data supports that demands for on-grid systems of the PV industry – which used to be dominated by off-grid systems – began accelerating in late 1990s, and they now account for the majority of electricity generated from PV (Mints 2013). According to an interviewee, a lot of contents of UL 1741 were later borrowed to develop IEC 62109, an international standard for the safety and reliability of BOS used in PV power systems.

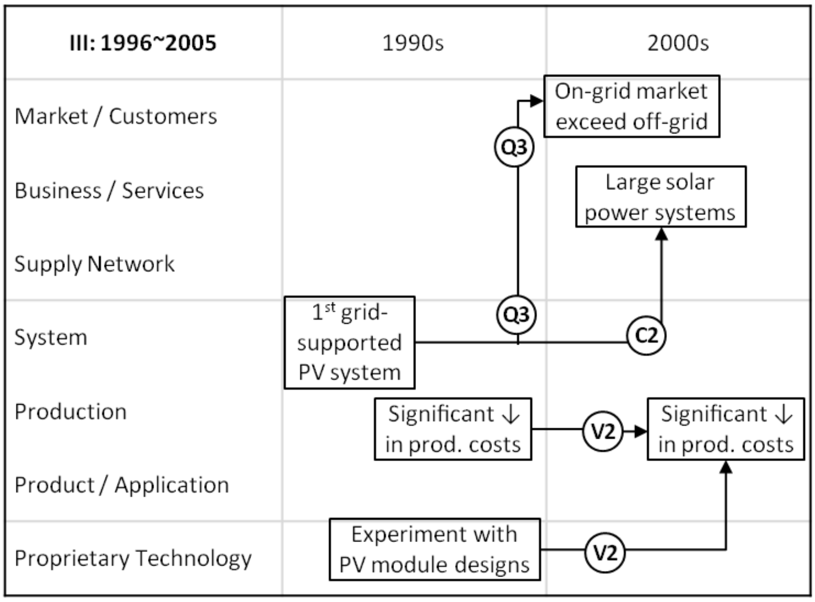


Figure 6.4 Innovation and standardisation of PV technology from 1996 to 2005

C2: Compatibility / interface standard for PV power systems

With the widespread of distributed energy resources in various forms (e.g., PV and wind), compatibility standards that establish successful linkages between those with electric power systems were needed (Basso 2009). IEEE 1547 was thus developed in 2003, by a TC which is mainly composed of utility companies and system developers (Ji 2009). Interviewees noted that this anticipatory standard not only allowed interconnections of quality distributed generators to larger grid systems, but also provided a common platform where advanced communications could be achieved among various products and systems, allowing utilities to better control the overall power system. As new technologies such as individual generators and system integrators are currently being added to larger power grid systems, more compatibility and interoperability standards will be required for a greater number of interfaces between various components and subsystems, noted multiple interviewees.

V2: Variety-reduction standard for module design

With the significant growth of PV market due to the introduction of larger power systems, de facto standards for module design appeared in early 2000s. Based on numerous engineering studies and experiments by manufacturers to identify the optimal design, standardised designs for various dimensions – such as number of cells in arrays, spaces between cells, and location of junction boxes – have emerged in the market, according to an interviewee from the industry. He noted that this responsive standard resulted in more economic production for manufacturers, by allowing them to use standardised equipment for handling PV modules of certain design.

6.2.1.4 Emergence of smart grid (2006~2016)

In late 2000s, the PV industry experienced massive growth in terms of production and market, as well as the advent of smart grid (see section 4.3.2 for details), which called for various standardisation activities led by a diverse group of stakeholders.

V3: Variety-reduction standards for mass production

There were urgent needs for standardisation related to production processes, so that communications between users and suppliers of PV manufacturing can be improved, and variability in manufacturing processes can be reduced to achieve economies of scale, noted

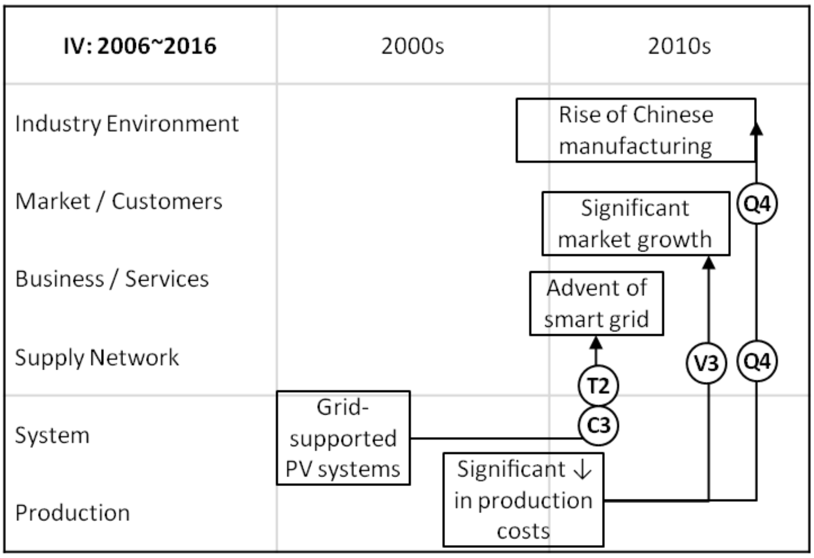


Figure 6.5 Innovation and standardisation of PV technology from 2006 to 2016

multiple interviewees. As many of the equipment and materials manufacturers in PV also had businesses in the semiconductor industry, existing standards developed by SEMI – i.e., a global trade association representing the semiconductor equipment and materials companies – were somewhat relevant to, but not entirely suitable for processes required by PV manufacturers, according to an interviewee. Hence, the TC dedicated for PV was established in 2006, to modify existing SEMI standards and develop new criteria, guidelines, and methods for PV-related process equipment, materials, or components (SEMI 2015). Interviewees noted that they lowered production costs, and also increased efficiency and consistency for process control, by improving traceability and optimising value-adding processes. An interviewee highlighted that such traceability is particularly important for a big industry, where most of technology improvement is done in regular production line rather than laboratory R&D. Thus acting as a driver of industrial learning curve practices for process control and reducing variability, SEMI standards led to significant expansion of the global PV market through more efficient production since late 2000s (EPIA 2011).

T2, C3: Terminology and compatibility / interface standards for smart grid

In order to further realise greater implementation of ICT for enhanced integration of various distributed generators with the grid, IEEE 2030 was developed in 2011, supporting data and knowledge exchanges through interfaces in addition to advanced communication provided by IEEE 1547 (Basso 2014). As the first systems level standard for an interdisciplinary area of smart grid, it also included definitions of key terminology used in the industry, facilitating communications among stakeholders across all tiers of the supply network, according to an interviewee. He also noted that increased systems complexity and diversity of smart grid will require more of such interface standards involving a great number of stakeholders with different backgrounds and expertise, for the successful interconnection of PV technologies with various other technologies and systems.

Q4: Quality / reliability standard for PV production systems

With the emergence of new PV manufacturers with mass production capacity, there were increasing concerns that existing qualification standards do not guarantee the consistency of high quality products being manufactured, according to multiple interviewees. IEC TS 62941 was thus recently published in 2016, specifying quality management systems required for PV manufacturers to increase the confidence that production modules will continue to meet the quality implied by passing the module qualification tests, e.g., IEC 61215 for crystalline silicon (Wohlgemuth 2014). Although there were identified needs for such information to increase consumer confidence in mass manufacturing – which may allow further production growth and cost reductions –, there was a lack of consensus on technical details among members of the committee, resulting in the development of a TS rather than an IS, noted an interviewee. Another interviewee highlighted that TS allows greater flexibility, so that the industry gets familiar to make better decisions until more data and information are gathered.

6.2.2 Other Patterns and Trends in PV Standardisation

Dimensions – *what, why, when, how,* and *who,* as identified in Chapter 4 – of key standardisation activities explored in the previous section are identified and summarised in Table 6.1. A number of trends and patterns have been observed on how these dimensions of standardisation have interacted with each other, resulting in complex and dynamic interplays with technological innovation. Due to the evolving emphasis on types of technology and innovation elements across different phases of innovation (e.g., from generic technology to products/applications, systems, and systems with higher complexity), various types of standards with different roles were required and developed by a variety of stakeholders. Thus reflecting changes in technological and innovation systems, these evolutions in dimensions of standardisation are discussed below.

Table 6.1 Dimensions of key standardisation activities for PV case study

Std	Code	What	Why	When	How	Who
T1, M1	NASA TM 73702	Science base, Infratechnologies, Generic technology	Terminology, Measurement/ testing	1977, Anticipatory/ Participatory	Technical report / Workshop agreement, Solution-describing	Research initiatives consisting of early PV stakeholders
Q1	JPL Block V	Generic technology, Product/applications	Measurement/ testing, Quality/ reliability	1981, Participatory	Performance/ Solution	De facto standards by national laboratory
M2	ASTM E891, E892, E948, E1039, E1125, E1144, E1362	Infratechnologies, Generic technology	Measurement/ testing	1982 ~ 1990, Participatory	Solution-describing	SSO
C1	IEEE 929	Product/applications, System, Business/ service	Compatibility/ interface	1988, Anticipatory	National standard, Solution-describing	SSO
V1	125mm wafer	Generic technology, Proprietary tech., Product/applications Production, Supply network	Variety-reduction	Early 1990s, Responsive	Performance-based	De facto standard by private companies
Q2	IEC 61215	Proprietary tech., Product/applications, Business / service, Market / customer	Measurement/ testing, Quality/ reliability	1993, Participatory	International standard, Performance/ Solution	FSO
Q3	UL 1741	System, Business/ service, Market/ customer	Quality/ reliability, Compatibility/ interface	1999, Anticipatory/ Participatory	National standard, Performance/ Solution	SSO
C2	IEEE 1547	System, Business/ service	Compatibility/ interface	2003, Anticipatory/ Participatory	National standard, Solution-describing	SSO
V2	Standard module design	Proprietary tech., Product/ applications, Production	Variety-reduction	Early 2000s, Participatory/ Responsive	Performance-based	De facto standard by private companies
V3	SEMI production standards	Production, Supply network, Market/ customer	Quality/ reliability, Variety-reduction	2010s, Anticipatory/ Participatory	Performance/ Solution	Consortium of suppliers
T2, C3	IEEE 2030	System, Supply network, Business/ service	Terminology, Compatibility/ interface	2011, Anticipatory/ Participatory	National standard, Solution-describing	SSO
Q4	IEC TS 62941	Production, Supply network, Market/ customer	Quality/ reliability	2016, Participatory	Technical specifications, Performance/ Solution	FSO

Trends in 'what' technology and innovation elements are relevant to standardisation

It is observed that different types of standards associated with different categories of technology and innovation elements were required at different stages of PV innovation. Mostly technology-supporting standards were developed in early stages of PV innovation where basic scientific research dominated; as PV systems developed and market expanded, first production-facilitating standards, and then market-enabling standards, were mainly developed. Such change of emphasis also matched well with four broad phases of the PV innovation journey (as discussed in section 6.2.1), reflecting the evolution of focus applications and systems across the history of PV technology. Nevertheless, new technology-supporting standards have been continually developed as technology improves and new technology appears, according to multiple interviewees. They were mostly in related technological areas other than core generic PV technology which is the basis of current PV products and systems – such as new PV materials (e.g., Organic PV (OPV)) and materials used in other parts of PV systems (e.g., inverters, BOS) – or in technologies used for new PV applications, such as building materials and automotives. New measurement and testing standards have also been recently developed, due to the improvement in test methods and techniques, as well as introduction of new measurement technologies (e.g., Light Emitting Diode), noted some interviewees.

Trends in 'why' standards are needed

Although standards playing the same role – but associated with different categories of technology – have repeatedly emerged at different phases of PV innovation, there was a general trend that standards with particular roles and functions dominated certain stages of the innovation journey: measurement and testing standards in early PV technology development, quality and reliability standards with the introduction of PV applications, and compatibility and interface standards with the widespread of larger systems. According to a number of interviewees, similar trends could be observed in other countries, as well as different types of PV technology, such as Concentrating PV (CPV).

Trends in 'when' to be standardised

As proposed by Sherif (2001), the timing of standards could be related to the intrinsic capabilities of the technology using the technology S-curve, as shown in Figure 2.2. While many standards were – either perfectly or partially – participatory standards, there was a general trend of following this model; anticipatory standards were mainly at the beginning of new technology, whereas responsive standards appeared after some market success. However, it was observed that such trends existed only within a single individual category of technology, and Sherif's (2001) model was not really appropriate for the entire innovation journey of PV technology that went through multiple levels of systems complexity. As different categories of PV technology with different systems levels appeared throughout its innovation (i.e., from generic technology of PV effects, to proprietary technology of PV modules, standalone PV applications, and large PV power systems), there were multiple S-curves, each representing a different set of functionality or performance/price ratios relevant to PV technology (e.g., efficiency of PV cells, performance of PV module designs, and energy output/production cost). It is thus found that the timing of standards is closely related to each lifecycle of the particular category of technology that standards are associated with.

Figure 6.6 represents a schematic diagram illustrating such relations of the timing of standards across multiple technology lifecycles for different levels of systems complexity. For example, the timing of early PV standards was mostly relevant with the lifecycle for the generic PV technology; participatory standards for measurement and testing methods were developed in parallel with the improvement of cell efficiency, whereas variety-reduction standards for wafer size appeared in response to numerous experiments and research on PV cells. On the other hand, the timing of the next set of standards was closely related to the lifecycle for the proprietary technology of PV modules; participatory standards for module quality were developed as PV module performance improved, whereas variety-reduction

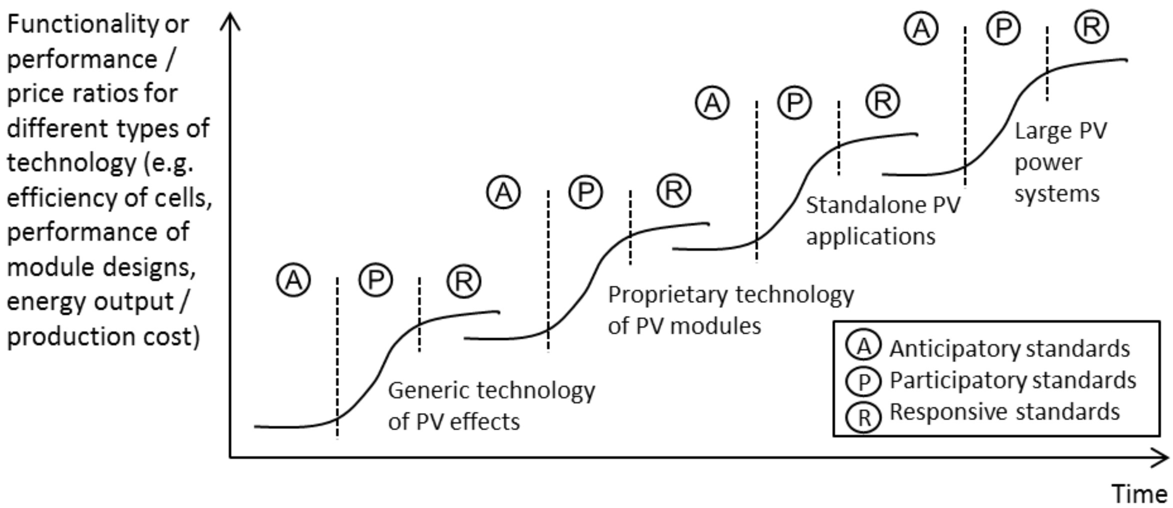


Figure 6.6 Timing of standards in relation with multiple technology lifecycles

standards for module designs were defined after the performance of PV modules and products had been demonstrated. Later, many compatibility and interface standards were defined at the introduction of particular applications or systems, since such anticipatory standards were needed to ensure that different components and products are connected and interoperable to each other. Hence, it is demonstrated from the longitudinal case study of PV over multiple technology lifecycles that standards with particular roles were developed at certain timings relative to technology lifecycles, of which the level of systems complexity (or category of technology) that standards are associated with.

Trends in 'how' to standardise

In the beginning of PV standardisation, technical reports were generated as results of research workshops, whereas more formal standards with high level of consensus, such as national and international standards, were developed by wider group of participants as the PV technology progressed. Recently, more technical specifications have appeared, due to increased challenges in achieving full consensus among even wider group of stakeholders involved in standardisation. It is also interesting to note that many of quality and reliability standards illustrated in the case study were both performance-based and solution-describing, specifying desired outcomes as well as how to perform test procedures to assess these performances.

Trends in 'who' is leading and involved in standardisation

In early days of PV, participants of standardisation were mostly researchers from national laboratories or academia, supported by government to perform research in this emerging area with high risks. As potential of PV applications were demonstrated, manufacturers and other companies – including materials / equipment suppliers and investors – started to participate; system-related stakeholders – such as utilities, system integrators, and installers – also joined, as on-grid systems market expanded. There are now a variety of stakeholders involved in PV standardisation, each coming from different organisations and disciplines, leading to increased complexity in negotiation and consensus-building, according to many interviewees.

6.3 Case Study Discussion

6.3.1 Insights from the Case Study to Justify Roadmapping Approach

The case study shows that five key dimensions of standardisation evolve and interact with each other, reflecting changes in technological and industrial systems. By disaggregating them in greater detail and integrating with holistic and integrated perspectives of the strategic roadmapping approach, the proposed framework is demonstrated to provide more comprehensive understanding of complex and dynamic interplays between standardisation and innovation. Incorporating strategic dimensions to be considered for management and foresight of standardisation, the roadmap-based framework is also expected to be useful for effectively addressing associated challenges and issues, as shown from the case study; these are discussed in this section.

Management and maintenance of a large stock of standards

The development and improvement of technology, such as materials, infratechnologies (e.g., measurement techniques and testing equipment), and application areas, all add complexities, increasing the number of standards required for the wide deployment of technology. Such proliferation of standards and standardisation projects leads to greater challenges of keeping track of them, noted multiple interviewees. In particular, it is important to adequately respond to technical changes – i.e., update or modify existing standards, or develop new standards – in a timely manner, as standards based on old technologies may create unnecessary barriers for new technologies or innovations to emerge by setting inappropriate criteria. According to multiple interviewees, CPV would not have been widely used if it were not the development of new standards specifically for it. As existing measurement standards for conventional PV modules were inappropriate for measuring performance of multi-junction cells used in CPV by creating artificial growth defects itself, CPV would have been considered as inferior to non-concentrating PV modules, possibly inhibiting its further development.

The issue of management and maintenance is becoming even more significant, as more standards are being interrelated to each other (e.g., IEEE 929 with UL 1741, and IEC 61215 with IEC TS 62941), due to the interdisciplinary, integrative, and systems-like nature of modern technologies. This is also evident from the bundling of standards; various types of standards associated with diverse levels of technology systems are increasingly incorporated into a single document. As it is inefficient to build consensus on all technical details while technologies evolve rapidly, there is a recent trend that standards are broken into small manageable pieces, and related ones are then grouped together, in order to increase the level of productivity and speed of standardisation processes. According to interviewees, this may increase not only the burden for standards writers, but also challenges in managing complex systems of standardisation; when a standard is revised, interrelated standards also need to be revised or updated. Therefore, a comprehensive, integrative, and holistic approach of roadmapping would be useful for managing the growing number of standards and related projects from a broader perspective, ensuring coherence and harmonisation of various standardisation activities in the industry.

Better Communication among Various Stakeholders

A number of interviewees noted the lack of effective communication to balance varied interests and needs of various stakeholders in current standardisation system. An interviewee recalled an example of UL 1699B (standard for arc-fault circuit protection), which was introduced without appropriate technology due to the lack of information sharing between researchers and code writers, leading to complicated processes of revision. Such absence of effective communication is even more problematic for de facto standardisation. According to another interviewee, needs for large PV modules used in building applications have not been properly communicated to manufacturers, resulting in inefficient standards in terms of both performance and production. As these de facto standards are now very much entrenched in the market, it is difficult to introduce new module designs without either changing production equipment or making it difficult to install, both of which increase costs.

Effective communication in standardisation is becoming a more significant issue, as technologies develop and industries grow. Many interviewees recalled that with the development of PV technology, there have been increasing needs for participation from a broader group of stakeholders, who do not usually sit on the same standardisation committee. Solar America Board for Codes and Standards (Solar ABC) was an effective forum of communication, establishing a dialogue among all key stakeholders – including manufacturers, sellers, buyers, users, and regulators of various PV materials, products, processes, or services –, noted multiple interviewees. It was also useful for bringing new perspectives that current members of existing SDOs may not be aware of, such as those of local fire officials, whose interests were not addressed despite their important roles in solar installations, noted an interviewee.

Therefore, more effective means of communication and information sharing are necessary among members of existing standardisation committee, as well as among stakeholders across the whole industry, according to multiple interviewees. Bringing participants from various organisations to create a common vision and build consensus through face-to-face meetings, the roadmapping approach may be useful in providing effective grounds for such discussion and consensus-building, where stakeholders are better connected and interacting with each other. Such improved communication and collaboration between research and industry may not only raise awareness of important standardisation issues to be addressed, but also promote technological innovation, by facilitating the development and transfer of new knowledge. This is particularly useful for new technology (e.g., CPV) where there is not much knowledge available with only a small number of stakeholders involved, noted an interviewee.

Collaboration and coordination among various SDOs

As PV technology becomes more complex, integrated, and interdisciplinary, various stakeholders from different areas and disciplines also needed to work together for standardisation, requiring various WGs, or even various SDOs, to collaborate and coordinate, noted multiple interviewees. For example, interviewees noted that standardisation of smart modules (i.e., PV modules connected with other electronic devices for better communication and control) requires technical expertise of both WGs for PV modules and systems. Without collaborative efforts, there is a risk of duplicative (or even contradicting) standards developed by different WGs or SDOs, leading to inefficiency and market confusion. A number of interviewees noted that UL 1703 and IEC 61730 are good examples of such duplicative standards, requiring manufacturers and suppliers to spend more time and resources to meet different requirements in different countries, despite their similarity in nature.

Therefore, collaboration and coordination among various SDOs are essential to effectively support innovation, particularly in complex and interdisciplinary technologies. Many interviewees highlighted that previous efforts of gathering various groups of SDOs involved in PV standardisation – such as PV Standards and Codes Forum, Solar ABC, and PV Manufacturing Consortium – were effective for such coordination, as they became aware of each other’s activities and could take appropriate, collaborative actions. Solar ABC was particularly useful in providing appropriate solutions for multidisciplinary issues that could not be addressed by a single SDO, added an interviewee. Similarly, roadmapping exercises may provide useful opportunities for such collaboration and coordination among different WGs in various SDOs.

Anticipation and timely development of standards

Another challenge of standardisation is the time it takes to develop optimal solutions and reach consensus among various stakeholders, particularly in fast-changing, multidisciplinary technologies; it takes more time and efforts to reach agreements on technical details, yet technologies evolve fast while building consensus. A number of interviewees noted the failure of IEEE 1262 – recommended practice for qualification of PV modules – due to the long time of its development; by the time it was published, an equivalent international standard (IEC 61215) already existed, making the standard obsolete. As there had been many other PV standards that became ineffective because they reflected outdated technologies, multiple interviewees highlighted the importance of considering the length of standardisation process together with the pace of technology development. In this regard, a holistic perspective of the roadmapping approach could be useful for anticipating and developing standards in a timely manner, by addressing alignment and sequencing issues related to various standardisation and other innovation activities with adequate considerations of time.

6.3.2 Reflections on Standardisation Mapping Framework

The case study demonstrates that systematic and future-oriented analyses of standardisation in support of innovation requires the multi-dimensional approach, considering all key aspects and issues – i.e., *what, why, when, how,* and *who* – captured in the standardisation mapping framework. It also suggests that a number of categories need to be added or modified to improve the framework, as discussed in this section.

‘What’ elements are associated with standardisation – addition of industry environment

Although general activities of the industry outside the innovation system in question do not directly influence standardisation activities, multiple interviewees noted that they still provide important contexts by serving motivations or backgrounds of other innovation activities, subsequently triggering standards-related activities. For example, space race and increased attention to energy security were important motivations for PV research in non-terrestrial and terrestrial applications, respectively; international landscape, such as policies and regulations by German government and a big wave of Chinese manufacturing, also had significant impacts on PV production and market in the US. Hence, it is appropriate to include 'industry environment' as a separate category for '*what*' innovation elements are relevant to standardisation.

'What' elements are associated with standardisation – refinement of policy & regulation

In addition to government policies and regulations, codes – i.e., specifications used in the design, build, and compliance process to construct safe, sustainable, affordable, and resilient structures (Martinez 2015) – are found to have significant influences on standardisation activities. A number of interviewees noted that changes in NEC Article 690 often triggered the development of new standards (e.g., UL 1699B outlining investigation for arc-fault circuit protection) or revision of existing standards (e.g., UL 1741 to include ground fault protection). Addressing safety codes that PV power systems installed in the US have to comply with, NEC Article 690 is typically adopted by local state governments for standardising their electrical practices (Wiles 2001). It is thus appropriate in 'policy & regulation' category to also consider such regionally enforced regulations and codes.

'Who' is involved in standardisation – refinement of stakeholders

There are various types of companies involved in PV standardisation, such as manufacturers, materials/components/equipment suppliers, utility companies, and system integrators. There are also various types of consumers who have interests in PV standardisation, including project developers, government agencies, installers, and investors. Multiple interviewees noted that it is important to engage more of such users in standardisation, as they not only use standards – either directly or indirectly – to ensure high quality, reliability, and safety of products and systems, but also provide useful insights from end-use perspectives.

It is also observed that consultants (both independent and from consultancy firms) and researchers (both from research organisations and academia) play particularly important roles in standardisation that requires highly technical knowledge. They thus deserve separate categories for stakeholders involved in standardisation in the context of technological innovation; whereas labour and NGOs – which play relatively minor roles, at least in the context of technological innovation – can be categorised as ‘others’.

In particular, a number of interviewees highlighted the significant role of independent consultants who, based on their long experience in the PV industry, now work as specialists in PV standardisation. While many new participants tend to focus only on specific areas of PV standards related to their core expertise, these independent consultants generally have comprehensive understanding of standardisation activities throughout the overall industry, by participating in multiple SDOs. As technical knowledge required for standardisation are becoming highly complex, people writing standards tend to focus more on specific areas of their expertise, so experts with such broad perspectives are becoming more important, noted interviewees.

6.3.3 Reflections on Process Model for Standardisation Foresight

This section discusses how the case study illustrates the usefulness of the current process model for standardisation foresight (proposed in Chapter 5) in addressing standardisation challenges, and provides additional insights to further improve the process model.

Step 0: Preliminary activities – identifying key persons managing overall processes

It is suggested that key experts with communication and management skills – such as independent consultants – may provide useful knowledge and skills for managing and organising overall processes of standardisation foresight, effectively addressing communication and coordination issues. A number of interviewees highlighted important roles of the administrator of Solar ABC in managing the forum; although he did not have detailed technical expertise in any one particular field of PV, he played critical roles in coordinating different interests of various stakeholders and facilitating the process of reaching consensus. It is also noted that experts with broad understanding in various areas of standardisation are particularly helpful in managing overall processes, by supporting effective coordination and collaboration of various SDOs. According to interviewees, people who participate in a number of different committees for PV standardisation (e.g., ASTM E44, IEC TC82, and IEEE SCC21) provided useful communication skills and technical knowledge across diverse fields of the PV industry; these are becoming critical as technologies become more complex, interdisciplinary, and systematic in nature.

Step 0: Preliminary activities – anticipating and engaging new stakeholders

The importance of recruiting new participants to better anticipate the future standardisation landscape is discussed in a few literature, as existing members of standardisation committees do not pay enough attention to external orientations, whereas actors in emerging fields do not have resources necessary to engage in multiple committees (de Vries et al. 2003; Gauch & Blind 2015). Engaging stakeholders from other relevant technologies with potential to be later adopted in innovation systems is found to be particularly critical as industries grow. Multiple interviewees highlighted the importance of being aware of new trends outside the current members' main expertise, as technologies other than core generic technologies continue to emerge from science base with the development of new technologies and applications. These include competing technologies such as new PV materials (e.g., OPV), as well as other components required for new applications (e.g., automotives). A number of interviewees also mentioned that analogous, cross-enabling technologies coming from different sectors (e.g., nanoelectronics) may provide useful perspectives and experiences for new infratechnologies (e.g., measurement techniques) or production processes, enhancing the current generic or proprietary technology.

Step 2a: Designing system architectures – designing architectures in terms of standards

Many interviewees highlighted the increasing need for having a broad structural view of the complex system, such as system architectures, by analysing how different components and technologies are connected to each other. An overall systematic view in terms of standardisation is also suggested to be useful, as such cross-reference can help identify interrelationships and linkages between standards, and also help keep track of how they change over time, supporting effective management and maintenance of complex systems of standardisation.

Step 3: Analysis of (inter)national environment – considering applications

It was noted by many interviewees that effective standardisation should take account of particular applications, as different applications may have different requirements (e.g., residential systems and large power plants requiring different power range), resulting in different optimal designs or solutions specified by standardisation. It may otherwise inhibit innovation by imposing unnecessary or insufficient barriers. For example, some interviewees noted that current qualifications standards require all PV modules to pass hail and static load tests, adding unnecessary costs for products inside buildings or even outdoor applications in some parts of the world. Another interviewee gave an example of OPV modules, whose adoptions are being delayed by damp heat tests of current standards, even though they may be more effective under certain conditions or environments.

Step 6: Review and follow-up – review of implementation

Standardisation is most likely to be effective when tasks divided among SDOs match well with their core competency and characteristics of members, according to multiple interviewees. They noted that the division of labour among SDOs was an important success factor, particularly in the early stage of PV innovation (e.g., ASTM for testing of cells and modules, UL for safety, and IEEE for systems). However, some interviewees noted that such division of labour does not always work out; as standardisation is essentially a business for SDOs, they often compete with each other to publish more standards. In addition, due to characteristics or structure of SDOs, it is possible that certain companies or countries may have dominance in representing particular interest groups, influencing and guiding standardisation for their own benefits, according to an interviewee.

As these may result in reduced efficiency and increased confusion due to duplicative or biased standards, it is important to review and evaluate implementation processes to ensure that standardisation tasks are appropriately assigned and properly carried out in various SDOs. Such reviews of implementation potentially need to be performed on a regular basis, either periodically or at defined points according to action plans, i.e., points when particular standardisation activities or other related activities are completed, suggesting needs for appropriate progress reviews. They can identify needs for any further action plans required due to results of implementation or changes in the standardisation landscape, and also needs for reiteration of roadmapping exercises to develop multiple mapping frameworks at various levels of granularity; these are further discussed in section 7.2.2.

6.3.4 Further Insights into Potential Roles of Government

The case study provides a number of additional insights regarding standardisation and relevant foresight activities, particularly potential roles of government. According to a number of interviewees, government should play important roles in initiating standardisation of emerging technologies, as industry is not strong enough to drive it themselves due to fragmented understanding and limited resources available. In the case of early stage of PV innovation, government, mainly through Department of Energy, took the responsibility to gather the industry on board and led collaborative efforts in standardisation (e.g., PV Standards and Codes Forum).

Such role of government in collaboration and coordination is important even after the industry takes off, especially in complex, multidisciplinary technologies where various stakeholders – from small to large companies operating in different technologies and markets – are involved in standardisation issues, according to multiple interviewees. Bringing a systems perspective to the overall industry, government has played active roles in coordinating various activities across different technological areas, and also organising initiatives that cut across the department and agency boundaries (Wessner 2011). A number of interviewees also noted that the engagement of federal government would be more effective in the US, as different codes and regulations are currently imposed by different local jurisdictions, increasing costs for installers and manufacturers. It is suggested by experts that such coordination and collaboration among various actors can be facilitated by developing an industry roadmap, which provides long-term consistency and predictability in government policy, allowing stakeholders to have confidence in their strategic decisions (Wessner 2011).

Government may also provide important support to ensure that constant efforts and resources are provided to develop appropriate standards in a timely manner, and make them publicly available, which are critical in supporting overall innovation systems. Such rationales for public good resources (discussed in section 5.3.3) are particularly relevant for infratechnologies. National laboratories – such as NIST and NREL – whose activities are heavily supported by government funding, provided important infrastructure and scientific foundations related to measurement and testing standards. Being technology agnostic, researchers at these institutes also provided unbiased technical information and assessment required to make decisions regarding other standardisation (Wessner 2011); government support is thus essential to ensure effective standardisation in support of technological innovation. A number of interviewees added that government subsidies for experts, particularly researchers from private organisations, to conduct research and participate in standardisation meetings would be also helpful, as companies are often reluctant to devote their resources into such long-term efforts that do not provide immediate results.

6.4 Implications from the Case Study

6.4.1 Refined Framework and Process Model

The revised framework and process model incorporating insights obtained from the case study are shown in Figures 6.7 and 6.8, respectively, with major changes in bold.

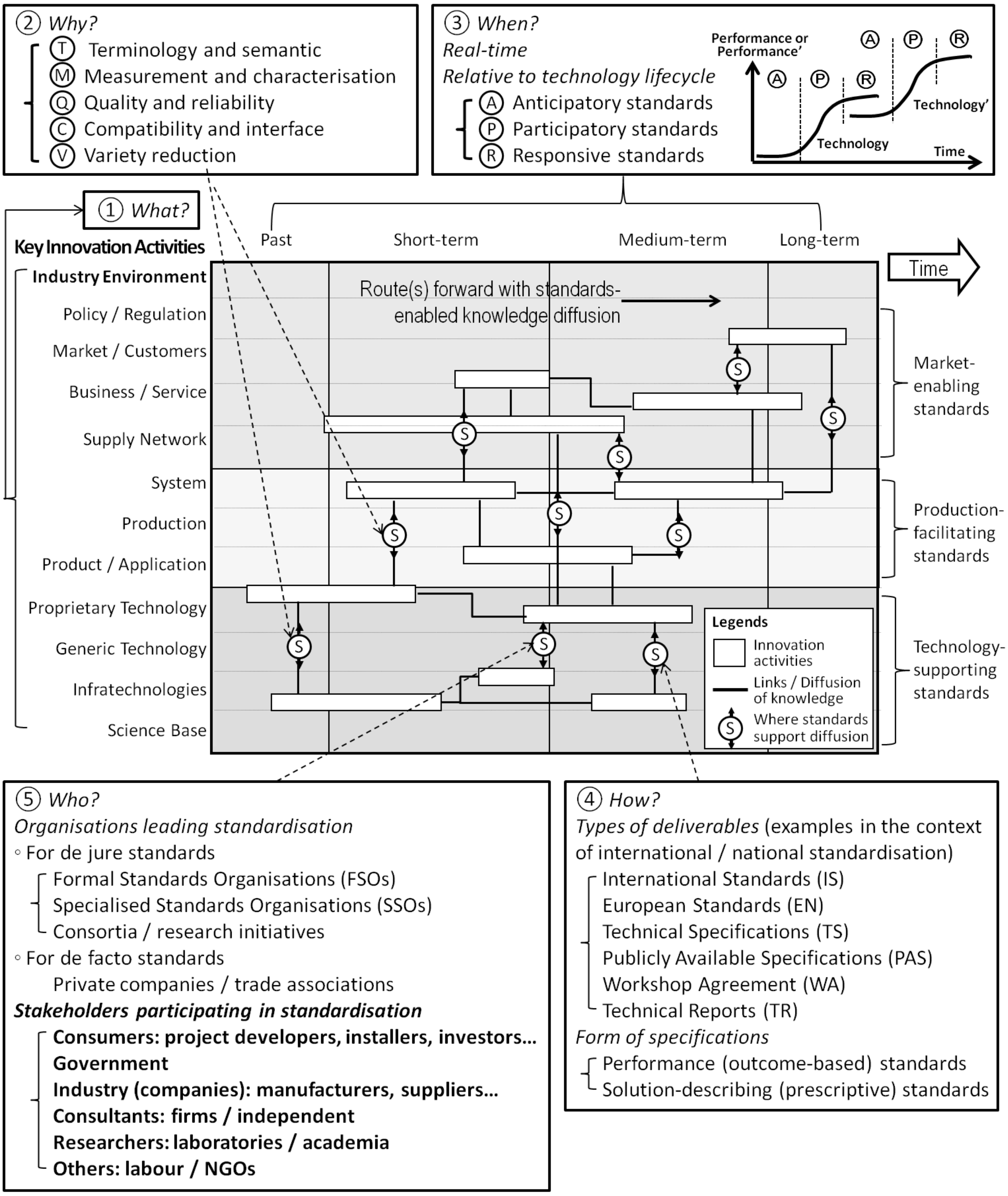


Figure 6.7 Standardisation mapping framework (ver.2)

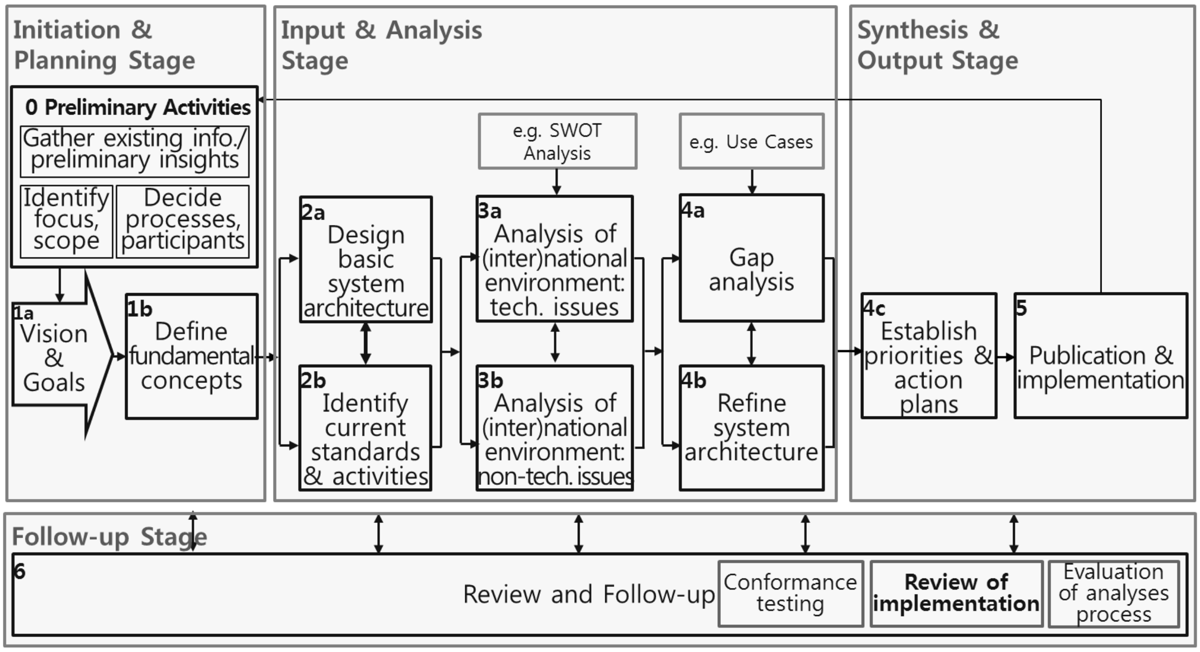


Figure 6.8 Process model for using the framework for standardisation foresight (ver.2)

With more detailed characterisation and articulation of important dimensions of standardisation, the roadmap-based framework is suggested to be useful for multi-dimensional analyses of complex and dynamic interplays between standardisation and innovation, as well as strategic foresight for standardisation. With minor revisions and refinements, the process model for using the framework for standardisation foresight is also expected to be an effective method of gathering and coordinating between stakeholders from various organisations and disciplines. The case study thus suggests potential areas of using the standardisation mapping framework, which are further discussed below.

Anticipating standardisation needs to support innovation

As discussed in both academic literature as well as the current case study, standardisation facilitates knowledge transfer and diffusion by codifying various new information and disseminating them among a variety of innovation actors. The case study demonstrates that such diffusion mechanism of standardisation – by interacting with various innovation activities performed by a variety of stakeholders – can be effectively captured and represented using the standardisation mapping framework. The framework can thus be used to anticipate where standardisation is further needed to facilitate innovation processes, by identifying potential barriers or gaps where such information can help enhance knowledge diffusion. Hence, the framework may be used to anticipate future standardisation needs and develop relevant strategies, supporting more effective and strategic foresight for standardisation.

Informing policymakers and business managers in making strategic decisions

By allowing multi-dimensional analyses of standardisation, the framework also provides greater insights into dynamics and transitions of complex innovation systems, helping the community make more informed decisions when developing innovation strategies. In particular, key characteristics and patterns of standardisation activities may be used as indicators or demonstrators of particular phases of the technology emergence and development, helping identify current status of the innovation journey. Such information can inform policymakers and other business managers to make appropriate strategic decisions in a timely manner, and also guide how various actors should coordinate with each other, supporting overall innovation systems more effectively. For example, the emergence of responsive standards may reflect the maturity of particular technology, thus the innovation community should prepare for new technology (with higher level of systems complexity) to develop. Such transitions across technology lifecycles in innovation systems are difficult to anticipate, making firms wait too long before investing in the new technology, so slowing down innovation processes, as argued by Tassey (2015). In this regard, the long-term, multi-cycle perspective of standardisation mapping framework may be useful in guiding innovation actors to acquire R&D skills and facilities required to migrate to the new technology in a timely manner, thus facilitating the innovation process.

6.4.2 Other Challenges and Issues with Standardisation

The case study identifies remaining challenges and issues regarding standardisation in the context of innovation, which are discussed in this section.

Challenges towards international standardisation

As the industry grows, there is an increasing attention towards international harmonisation of standards to support international markets. An interviewee noted that failing to conform international standards may isolate companies in national markets, thus retarding the national industry, as was the case in Japan. However, developing international standards is extremely challenging, not just because of bureaucratic procedures to achieve consensus among a large number of participants, but also due to different philosophical approaches to standardisation in different countries, according to multiple interviewees. For example, the US adopts a market-based approach, whereas European countries rely more on jurisdictions. It is shown from the case study that such challenges are becoming even more significant as industry develops, because of different cultures and legacies of how electricity infrastructure has evolved. An interviewee also highlighted that the longer it takes to reach international consensus, the more entrenched each national standards become, making it more difficult to make countries to accept international standards.

Balance between flexibility and stability

As noted by various academic scholars (e.g., Hanseth et al. 1996; Lehr 1995), standardisation is often about the balance between flexibility and stability. Some interviewees, particularly from manufacturers, suggested that problem-, or performance-based standards should be written whenever possible, in order to open up future possibilities allowing further innovation. They claimed that prescriptive or solution-describing standards, on the other hand, can potentially inhibit innovation by making it difficult to respond to technology evolution. Other interviewees, particularly from research laboratories and user groups, argued that more stringent standards are needed, as such flexibility can result in ambiguities and confusions in interpretation, reducing benefits of standardisation. Different levels of flexibility and stability would thus be needed for different standardisation, which should be explored in the future.

6.5 Concluding Remarks

Demonstrating the usefulness of the standardisation mapping framework developed in Chapter 4 in multi-dimensional analyses of standardisation over an extended period of time, the in-depth case study of PV technology confirms that five dimensions of standardisation – *what*, *why*, *when*, *how*, and *who* – all need to be appropriately considered for systematic and future-oriented analyses of standardisation. The case study also provides detailed insights for these dimensions and their sub-categories, leading to the minor improvement of the framework. In particular, it (i) helps refine innovation elements associated with standardisation, particularly industry environment and policy & regulation; (ii) identifies additional types of stakeholders involved in standardisation, such as users, trade associations, and independent consultants, and; (iii) provides longer term, multi-cycle perspectives in analysing relationships between roles of standardisation and its timing relative to technology lifecycles. In addition, the case study demonstrates the potential usefulness of the process model developed in Chapter 5 for standardisation foresight, and also identifies a number of useful practices that may be additionally incorporated, such as identifying key persons managing overall processes, engaging new stakeholders from relevant technologies, and review of implementation. Last but not least, the case study provides useful insights regarding potential roles of government, such as driving standardisation initiatives for emerging technologies, providing constant efforts and resources for public goods, and supporting collaboration and coordination among various stakeholders of complex, multidisciplinary technologies. Although only minor modifications to the framework and the process model indicate their relative stability and robustness, their practicality and usability will be further verified in the next chapter.

7. VERIFICATION OF FRAMEWORK AND PROCESS MODEL

This chapter focuses on the verification of the refined standardisation mapping framework and process model for using it, both presented in Chapter 6. Case studies in the previous chapters have demonstrated significant potential value and relative stability of the framework and process model, suggesting that no further case studies are needed within the scope of the current thesis. Notwithstanding this, further testing and validation of the framework and process model were carried out through interviews with experts across a broader range of technology domains, sectors, and regions. Although the findings did not result in any significant changes to the framework and process model, their robustness and completeness were demonstrated, and some existing features and activities were clarified. In addition, experts provided further insights and useful suggestions on various issues regarding the general practicality and operationalisation for using them for standardisation foresight, including the role of government and how to present the framework and process model.

7.1 Overview of Verification Interviews

The combination of multiple exploratory case studies in various contexts (discussed in Chapters 4 and 5) and a single in-depth case study of PV technology (discussed in Chapter 6) sufficiently demonstrates the value of the roadmap-based framework and process model for systematic and strategic analyses of standardisation in support of innovation. As the case study of PV suggested only minor modifications of the framework and process model, providing strong evidence for their relative stability and robustness, it can be concluded that no further in-depth case studies are needed within the scope of the current thesis. Nevertheless, further interviews with standardisation experts – with various backgrounds, in terms of nationality, technical domains, and organisational perspectives – may supplement previous studies for the purpose of triangulation, testing, and generalising, as discussed in section 3.4. Overcoming any potential limitations – which may exist due to the small number of case studies despite careful selection – they may also provide further tests for general practicality and usability of the refined framework and process model (ver. 2) presented at the end of Chapter 6. Interviews specifically aimed to achieve the following objectives:

- Verify the terminology adopted in the framework and the process model for using it for standardisation foresight.
- Identify any particular advantages of the framework and process model (compared to existing practices).
- Identify potential areas of improvement and possible limitations of the framework and process model.
- Explore the practicality and utility of the framework and process model, including any suggestions to facilitate their management and operationalisation in practice.

7.1.1 Participant Selection

Personal e-mail invitations were sent out to potential interviewees, who were selected among participants of the following standardisation-related conferences:

- European Academy for Standardisation Research (EURAS) Conference held in Copenhagen, Denmark, in June 2015;
- International Cooperation for Education about Standardisation (ICES) Conference held in Seoul, Korea, in August 2015; and
- IEEE International Conference on Standardisation and Innovation in Information Technology (SIIT) held in Sunnyvale, US, in October 2015.

The first round of interviews was conducted with six participants who agreed to meet during these conferences. The second round of interviews was performed – via either phone or e-mail – with seven additional experts who were approached through follow-up e-mails, “snowball sampling” (Goodman 1961), and using the researcher’s network; no further interviews were needed as a point of saturation has been reached (see section 3.6.2). In addition, discussions with five experts who participated in the aforementioned conferences provided useful insights for the purpose of this verification study. Although these were not as comprehensive as formal interviews, conversations were guided by similar protocols, with particular attention given to the verification of the proposed framework and process model.

Table 7.1 lists profiles of experts who provided insights for this study through interviews and discussions. They were deliberately selected to cover various perspectives, in terms of

Table 7.1 Profiles of experts who provided insights into verification study

Study Type	Expert #	Organisation	Nationality	Experience / Perspective in Standardisation	Participating SDOs
Face-to-face Interviews	1	KSA	Korea	Strategic management in SDO	National FSO
	2	ETRI	Korea	Participation as researcher from laboratories	National FSO, SSO (electrical)
	3	Erasmus University	Netherlands	Academic research in standardisation	
	4	Technical University Berlin	Germany	Academic research in standardisation	
	5	KSA	Korea	Strategic management in SDO	National FSO
	6	Korea University	Korea	Academic research in standardisation, Participation as academic	National FSO
E-mail Interviews	7	Independent consultant	US	Participation as consultant	SSO (ICT), consortia
	8	RWTH Aachen University	Germany	Academic research in standardisation, Participation as academic	SSO (ICT), consortia
	9	ACE Consulting	Netherlands	Participation from industry	National / Regional / International FSO (ICT)
Phone Interviews	10	BSI	UK	Strategic management in SDO	National FSO
	11	AT&T	US	Participation from industry	SSO (ICT), consortia
	12	Airbus Defence and Space	France	Participation from industry, Strategic management in SDO	International FSO (space, innovation management)
	13	CEN / CENELEC	Belgium	Strategic management in SDO	Regional FSO
Discussions / Conversations	14	ETSI	France	Strategic management in SDO	Regional FSO
	15	NIST	US	Strategic management in government agency	
	16	NIST	US	Strategic management in government agency	
	17	Independent consultant	US	Participation from industry (in the past)	SSO (ICT), consortia
	18	Delft Institute for Research on Standardisation	Netherlands	Academic research in standardisation	

organisational backgrounds (including industry, research laboratories, academia, government, and SDOs), participating SDOs (including FSOs, SSOs, and consortia), and countries with different strategic approaches to standardisation (including government- and industry-driven) as well as different technological and standardisation capabilities. Although many of them are from ICT-related domains among other technological areas, this is inevitable as there are the most needs for standardisation; other interviewees from SDOs and academia complement this, as they have more general understanding of standards across various domains of technology. Such variations demonstrate the generality of the framework and process model across a broader range of technology domains, sectors, and regions.

7.1.2 Interview Description

All interviewees were provided with a briefing note – with a summary overview of the roadmap-based framework and process model – prior to actual interviews, in order to familiarise them with the approach, and to stimulate their thinking in advance. At the beginning of each interview, more detailed explanations of each of their features and elements were provided again, with the help of visual aids. Semi-structured interviews then followed, inviting their opinions on the following key topics:

- Relevance and validity of features of the current framework and process model.
- Potential improvements, limitations, and additional concerns of the framework and process model.
- Practicality and utility of the framework and process model for standardisation foresight.

These are discussed in the following sections.

7.2 Verification of Framework and Process Model

Interviewees generally agreed with the current framework and process model, and identified no significant changes that need to be additionally made; these are thus not replicated here. Nevertheless, they provided some useful insights, which helped clarify and articulate existing features of the framework and process model, which are discussed in this section.

7.2.1 Reflections on Standardisation Mapping Framework

Interviewees generally agreed that the holistic and integrated approach of the roadmap-based framework has significant value in providing more comprehensive understanding of various aspects of standardisation in the context of technological innovation. They also validated the need for detailed categorisation and articulation of various dimensions of standardisation incorporated in the framework. For example, an interviewee noted how measurement standards can be associated with either ‘science base’ or ‘infratechnology’, demonstrating various levels of technology elements relevant to standards with similar roles and functions. Although interviewees mostly agreed with dimensions and sub-categories presented in the framework, they suggested a number of minor revisions and clarifications to make it more appropriate and useful for systematic and future-oriented analyses of standardisation.

‘Why’ standardisation is needed

Although no new types of standards (in terms of their roles and functions) were identified, demonstrating stability and validity of this dimension, a number of interviewees suggested different terminologies for certain categories of standards, such as adoptability standards, product certification, and quality management standards. Some of these do provide more accurate representations of roles and functions of standardisation in particular contexts or technological domains, even though there are advantages of following existing categories that are conventional and more commonly used. It is thus advised that more specific labels for the ‘*why*’ dimension of standardisation are used in practice, reflecting language and terminology used by the community developing the mapping framework.

‘Who’ is leading standardisation

An interviewee noted that there are various types of FSOs. For example, being the national FSO of the UK, BSI is a non-profit distributing company incorporated by Royal Charter, whereas national FSOs in many other countries (including those in Europe and Asia) are government organisations; potential implications of such differences are further discussed in section 8.2.2. Every country has different history and culture of standardisation systems and its governance, reflecting variations in their institutional and industrial systems. It is thus not straightforward to identify common characteristics of various national FSOs.

Nevertheless, the most essential feature of national FSOs that distinguish them from SSOs is their national representations in regional or international FSOs; an expert from an SSO noted that due to such differences, FSOs and other SDOs (such as SSOs and consortia) focus on standardisation activities that are different in terms of their underlying value. For example, ETSI, an European FSO in the telecommunications industry whose standards often become mandatory requirements in Europe, concerns management and standardisation of resources with large value (e.g., defining frequency spectrum for wide networks) of which optimisation is costly. On the other hand, SSOs such as IEEE develop standards that are less regulatory, focusing on resources with relatively small underlying value (e.g., local networks). Such differences are due to different levels of authority and resources required for standardisation. There is preliminary evidence that they also result in different types of standards (in terms of their roles and timing relative to technology lifecycles) developed by different types of SDOs (Sherif 2001), which requires further exploration in future research.

‘Who’ is involved in standardisation

Various ways of further categorising stakeholders involved in standardisation were suggested. An interviewee highlighted that stakeholders can be categorised according to different roles and interests, including creators, implementers, users, and self interested parties. Another interviewee also suggested that the private sector industry (i.e., companies), as one of the most important types of stakeholders (at least in terms of the percentage of participation), may be further classified according to various factors, such as size, sectors, and interests. Although these are important characterisations that may provide useful insights regarding how different types of stakeholders make different contributions to standardisation, it is not the focus of the current thesis to explore in that level of detail; thus no further classification is provided here, but it may be an interesting issue to explore in future research (see section 8.3.2).

It was also suggested by an interviewee that individuals or institutions that offer training and education about standards may also have interests (though often marginally), as standardisation involves not only development, but also appropriate implementation and uses of standards. However, such educational activities are mostly provided by SDOs or users of standards, thus educators are not separately categorised here.

7.2.2 Reflections on Process Model for Standardisation Foresight

Many interviewees agreed that the roadmap-based process – where a group of experts are gathered together to discuss and build consensus – would provide a useful ground for discussion among various stakeholders, which is essential for strategic management and foresight of standardisation. They also generally agreed with activities represented in the process model; according to an interviewee from an SDO,

> *"Most of steps and activities included in the process (model) are very much what we [SDOs] actually do in foresight (analyses) to anticipate standardisation gaps and develop related strategies."*

In addition, they verified that some tools and activities newly introduced in the process model, including preliminary activities and system architectures, are particularly useful to address the increasing complexity of modern technologies involving a diverse group of stakeholders with different perspectives and technical backgrounds. Nevertheless, a number of minor suggestions were also provided to clarify and improve the process model; these are reviewed in detail below.

Step 0: Preliminary activities

An interviewee from a regional FSO highlighted the need to identify an appropriate scope of analysis in terms of whether it is national, regional, or international, as it has significant implications for the structure and process of standardisation foresight activities. According to her, national FSOs (e.g., BSI and DIN) tend to take more bottom-up approaches, focusing on anticipations of standardisation gaps from technology perspectives; whereas regional or international FSOs (e.g., CEN/CENELEC) tend to take more top-down approaches, focusing on alignment of these standardisation activities with regulations and other policy-related issues. Such differences are inevitable due to different needs and purposes of strategic analyses in SDOs at different levels, and may require different participants and categories of dimensions in the framework being developed. Different approaches – either top-down or bottom-up – may also be adopted in different countries having different institutional systems; such issues and their implications are further discussed in section 8.2.2.

Another interviewee suggested that additional efforts to publicise and raise awareness among a wider group of community are needed to promote their engagement in standardisation foresight activities. Although experts are generally approached within existing networks of

SDOs, this may not be enough to anticipate new challenges and issues in fast-evolving areas, she noted. Such efforts thus may help identify and engage new institutions and entities to be involved from outside the existing network.

Step 1a: Identify vision and goals

A number of interviewees verified the importance of setting common goals at the beginning of foresight analyses, as lack of such goals may significantly hinder cooperative efforts for more effective and strategic management of standardisation. They noted that various stakeholders, especially private sector businesses, often pursue their own interests and goals that are different from those of government or greater public interests in standardisation. Hence, common goals of standardisation to support overall technological and industrial systems need to be agreed in advance, prior to any strategy development.

Step 2a: Design basic system architectures

Many interviewees confirmed the usefulness of developing system architectures in providing structural overviews of complex systems, particularly for multidisciplinary technologies (e.g., smart grid, e-mobility, and cyber-physical systems) with a variety of stakeholders involved. A number of interviewees added that it may be challenging to have a single standardisation mapping framework for such complex, multidisciplinary areas; this actually justifies the use of the roadmapping approach, whose potential flexibility and scalability have been demonstrated in many literature and practice (e.g., Phaal & Muller 2009; Phaal et al. 2012). As modern technological systems consist of a large number of technology elements at different levels (including generic technology, infratechnology, product, and system), it may be more appropriate to develop multiple frameworks at various levels of granularity. Designing basic system architectures can support architecting the framework, helping identify the right scope and level of categories to be used in vertical and horizontal axes of each standardisation mapping framework (i.e., '*what*' elements are relevant to standardisation, and '*when*' standardisation is needed); it thus provides an important link between the framework and the process model.

Figure 7.1 presents structured visual representations to support the dissemination and synthesis of such multiple frameworks generated during standardisation foresight exercises, adopting the idea of multiple roadmaps at various levels of granularity suggested by Phaal et al. (2012). For complex, multidisciplinary technological systems under consideration,

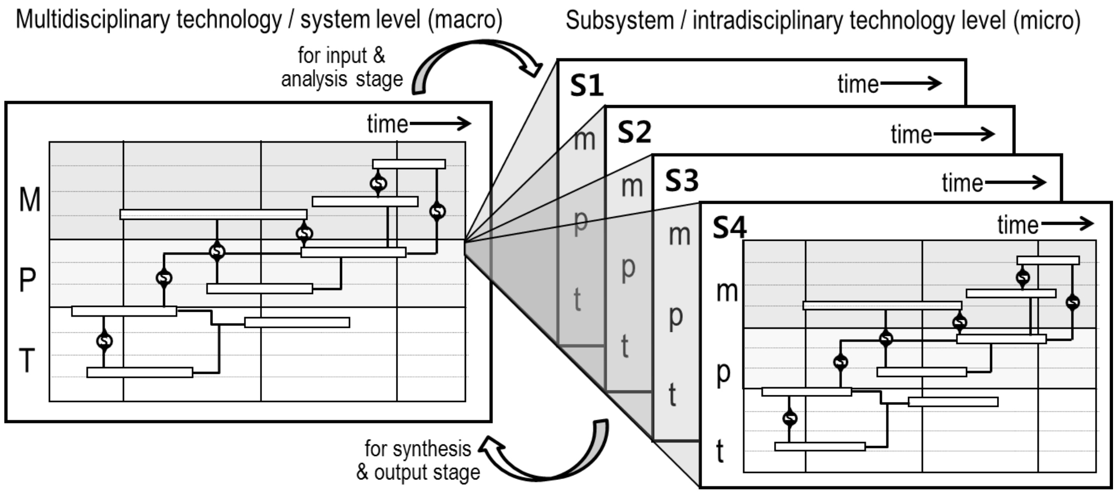


Figure 7.1 Structured visual representations for dissemination and synthesis of multiple standardisation mapping frameworks at various levels of granularity

multiple system architectures may be designed for smaller subsystems that are interconnected to each other, as discussed in section 5.3.1. Similarly, multiple standardisation mapping frameworks with more detailed levels of granularity can be designed, each focusing on a particular subsystem or intradisciplinary technology unit with different lifecycles. With more refined level of categories for '*what*' and '*when*' dimensions of standardisation, they help identify the most relevant lifecycle (e.g., product, technology, or systems) as well as participants who are experts in particular subsystems or technology domains; they thus provide a more detailed and micro level of analysis during the input and analysis stage. These independently developed roadmaps can be later integrated during the synthesis and output stage, resulting in a more comprehensive and integrative mapping framework from macro-level system perspectives. It is important to review the final integrated roadmap, to identify and explore crosscutting issues, and to ensure consistency and coherence across different domains and subsystems.

Dissemination and synthesis of multiple frameworks developed by different WGs or SDOs are particularly useful for coordination and collaboration among communities that focus on independent, yet related technological domains. For example, experts noted particular challenges associated with managing standardisation in the fields of big data, cloud computing, and internet of things, which have evolved from different technological domains with different cultures and legacies, yet are all interrelated with each other. Such challenges are even more increasing, as many of these standardisation activities are independently led by consortia in private sectors. Developing multiple frameworks for each domain and integrating them can facilitate collaboration, ensuring coherence and harmonisation of standardisation across various disciplines that are interrelated to each other. It is, however, to be noted that such collaborations need to take into account a number of additional considerations, such as efforts to use compatible system architectures and common terminology, in order to ensure the compatibility across multiple frameworks. Such issues regarding the dissemination and synthesis of multiple frameworks may need further research, including the sequencing and iterations of roadmapping at various levels of granularity.

Step 2b: Identify current standards and standardisation activities

When exploring current standardisation activities relevant to the technological system under consideration, it is important to constantly search for activities in new SSOs and consortia, according to multiple interviewees. Such activities are particularly needed when developing standardisation strategies for converging, multidisciplinary areas, where new SDOs often emerge, as existing organisations are neither appropriate nor effective to respond to the rapid development of new technologies and markets. The nature and characteristics of these SDOs also need to be analysed in detail, so that the most suitable organisation for leading particular standardisation activities can be selected when developing action plans in step 4c.

Step 3: Analysis of (inter)national environment: technical / non-technical issues

A number of interviewees highlighted needs to analyse both technical and non-technical issues in multinational regional contexts (e.g., Europe, Asia, and Africa). In the current environment of global economy, many standards – particularly compatibility and interface standards in ICT-related industries – are desired at the international level, yet this is extremely challenging due to differences in standardisation cultures and legacy systems of different countries. There are thus increasing efforts towards regional standardisation among countries who share similar economic and cultural environments; in addition to efforts in Europe, recent examples include East African Standards Group, and Standardisation Organisation for the Arab States of the Gulf, noted a few interviewees.

Step 4c: Establish priorities and action plans

During the development of action plans, it is important to consider all strategic options, in order to come up with the most appropriate and adequate action plans to address current standardisation challenges. An interviewee noted that sometimes it may be more effective not to develop any standards, and leaving room for further variation and differentiation may be more beneficial to the overall innovation system. Another interviewee also highlighted that committees often jump to conclusions, possibly resulting in inferior standards. Assessing potential advantages and disadvantages of all strategic options in great detail, always including ‘no standardisation’ as an option, is thus suggested before reaching a solution.

A number of interviewees also suggested needs to consider other issues, such as various stages of standardisation and varying stakeholders participating at each stage, when developing detailed action plans. Standardisation goes through various stages of development – such as requirements elicitation, development of base standard, and profiling – and different types of stakeholders may contribute to different phases of standardisation; for example, users define requirements, whereas implementers participate in profile development.

Step 6: Review and follow-up

A number of suggestions were given for the review and follow-up step. An interviewee noted that during conformance testing of newly developed or modified standards, education for implementers and users of standards are needed to ensure that they are able to adapt to and make the most out of these changes. Another interviewee also suggested performing evaluation and assessment of outputs of strategic actions in terms of various factors, including: whether they match initial goals and objectives (in terms of functions to be fulfilled and various stakeholder interests to be met), and their impacts on financial and social value. There would be a variety of methods and rationales for conducting such evaluations; however, it is beyond the scope of the current thesis to explore this complex topic. Nevertheless, such evaluations would be helpful for future analyses when deciding what further actions are needed for effective standardisation, thus are included in the process model. In order to better incorporate these activities – i.e., education and evaluation – in step 6, ‘conformance testing’ is renamed as ‘review and assessment of outputs of strategic actions’.

In addition, it is suggested by an interviewee that identifying review questions to be asked before moving on to the next step of the process model would be helpful to provide guidelines for individuals or organisations managing the overall process of foresight analyses, ensuring that all necessary activities are performed appropriately and adequately at each stage. A list of review questions is thus proposed and shown in Table 7.2.

Table 7.2 Review questions to be asked at each step of the process model

Steps	Detailed Activities	Review Questions
0: Preliminary activities	- Gather existing information / preliminary insights	- Are all existing reports and foresight analyses on relevant issues gathered? - Are additional insights gathered from participants?
	- Identify scope	- Are focus, scope, and boundaries (in terms of various aspects, including domain and time) of the roadmap clearly identified with an appropriate level of analysis?
	- Decide processes & participants	- Are processes of the foresight exercise clear and appropriate? - Do selected participants represent a balanced view of the system? - Are enough publicising efforts carried out to raise awareness in a wider community and identify all appropriate participants (including potential new participants in related technologies)? - Is the key person managing the overall process of foresight identified?
1a: Identify vision & goals	- Identify vision, goals & objectives	- Are common vision and high-level goals agreed among participants?
1b: Define fundamental concepts	- Define fundamental concepts	- Are common definitions and fundamental concepts (including stakeholders involved) defined for common understanding of the system?
2a: Design basic system architecture	- Design basic system architectures	- Are basic system architectures with appropriate level of detail and flexibility developed and broadly agreed among participants? - Are appropriate categories for vertical and horizontal axes of the standardisation mapping framework decided, for each of multiple frameworks at various levels of granularity?
2b: Identify current standards	- Identify current standards & standardisation activities	- Are all existing standards and standardisation activities in relevant SDOs (including emerging SSOs and consortia) identified? - Are they accurately mapped against basic system architectures, using terminologies and definitions commonly used by the community?
3: Analysis of (inter)national environment: technical / non-technical issues	- Analysis of national / international environments (e.g. SWOT analysis)	- Are various issues and challenges (in terms of technology, applications, markets, industry, regulations, policies, and intellectual properties) explored to analyse the current standardisation landscape (in national / regional / international contexts), relevant to the technological system in question, as well as other related domains / markets with potential impacts?
4a: Gap analysis	- Gap analysis (by developing use cases)	- Are key standardisation gaps identified through sound and thorough use case analyses?
4b: Refine system architecture	- Refine system architectures	- Do refined system architectures represent more detailed, realistic, and widely agreed structural overview of the system, meeting initial visions and goals?
4c: Establish priorities & action plans	- Establish priorities based on strategic importance	- Are priorities of identified gaps assessed against important criteria, such as strategic importance, urgency, and estimated timeframe?

	- Develop and review action plans	- Are all appropriate strategic options (including 'no standardisation') considered? - Are detailed action plans ('what' actions to be done by 'when' and 'who' in each stage of standardisation) decided for each priority? - Are these action plans in line with strategic positions of the industry / market? - Are these action plans consistent and coherent across related domains / systems?
5: Publication & implementation	- Review process	- Are there further opportunities where wider stakeholders are engaged through reviewing results of foresight analyses?
	- Execute action plans	- Are action plans well communicated and delivered to responsible organisations and stakeholders?
	- Guidelines for strategic decisions	- Are results of standardisation foresight analyses published and appropriately communicated to other relevant organisations?
6: Review & follow-up	- Evaluation of strategic analyses process	- Are feedbacks from participants obtained on the overall process of foresight analyses? - Can the foresight process be improved based on these feedbacks?
	- Review of implementation	- Are action plans appropriately carried out and implemented by responsible organisations and stakeholders? - Are these progress reviews performed on a regular basis?
	- Review and assessment of outputs of strategic actions	- Are implemented strategic actions reviewed to examine their completeness and effectiveness? - Are necessary educations regarding implementation of new / revised standards carried out appropriately? - Is effectiveness of outputs of strategic actions (in achieving goals and objectives) evaluated for further actions or future analyses?

7.3 Practical Implications from Verification Interviews

Verification interviews also provided useful insights regarding the practicality and operationalisability of the framework and process model, which are discussed in this section.

7.3.1 Practicality of Framework and Process Model

Many interviewees confirmed the usefulness of the systematic framework in analysing complex dynamics of standardisation in the context of technological innovation, by having an holistic and comprehensive overview of systems from various perspectives; according to an interviewee from academia,

> *As various aspects and dimensions of standardisation are interconnected to each other, it is more effective to analyse them in a holistic and integrative way, rather than independently* (translated from Korean by the author).

They also agreed that the systematic approach of the roadmap-based framework has potential to be used as a practical tool for guiding standards organisations in anticipating standardisation needs and developing relevant strategies. This is because of its ability to capture the multi-dimensional nature of standardisation, as well as various perspectives of stakeholders with diverse backgrounds and interests. Multiple interviewees particularly highlighted the effectiveness of the layered format of framework in capturing various perspectives of different stakeholders to be addressed, allowing their engagement and consensus-building to identify common solutions. This is important as different innovation actors (from technological innovators to regulators) often have different interests, yet generally do not talk to each other, resulting in considerable barriers and challenges in overall innovation systems, according to various interviewees.

Multiple interviewees noted that such a systematic perspective of standardisation mapping framework would be particularly useful in addressing variations, complexities, and uncertainties associated with emerging technologies, by linking standardisation more closely with other innovation activities (including R&D). They confirmed that the process model also provides a useful process for organisation and management of standardisation foresight analyses, addressing additional challenges associated with complex emerging technologies that intrinsically exist in the roadmap-based framework.

Many interviewees agreed that such usefulness and advantages of the framework and process model are considered to be increasingly important, as modern technologies and their standardisation are becoming more complex and interdependent on each other; an interviewee with expertise in ICT standardisation noted that

> *There are increasing challenges to develop a large number of standards in highly complex areas where different technologies, both hardware- and software-related, are interacting with each other and fast-evolving at the same time. A systematic and integrative approach is thus needed for their strategic management and foresight analyses, supporting innovation more effectively.* (translated from Korean by the author)

Other factors, such as increasing globalisation, fast pace of technological advancement, and the rise of emerging economies, all add to complexities and uncertainties associated with standardisation, increasing the value of the systematic framework and strategic process model for using it, according to experts from various organisations and disciplines.

7.3.2 Guidance for Using Framework and Process Model

Insights from verification interviews also provided useful guidance for using the framework and process model for standardisation foresight analyses in practice. First, a number of interviewees suggested cross-referencing between the standardisation mapping framework and the process model for using it. By visually representing relationships and linkages between the two, it may provide useful guidance for practitioners who actually use them. Hence, Table 7.3 is developed, identifying dimensions of standardisation that are particularly relevant for each step of foresight processes, thus highlighting which dimensions require the most significant attention to be paid.

Table 7.3 Relevant dimensions of standardisation for each step of the process model

Steps	What	Why	When	How	Who
0: Preliminary activities	*				**
1a: Identify vision & goals	*	*	*		
1b: Define fundamental concepts	**				**
2a: Design basic system architecture	**				
2b: Identify current standards	*	*	*	*	**
3a: Analysis of (inter)national environment: technical issues	** (technology / production)				
3b: Analysis of (inter)national environment: non-technical issues	** (market)				
4a: Gap analysis	**	**			
4b: Refine system architecture	**				
4c: Establish priorities & action plans	*	*	**	**	**
5: Publication & implementation					*
6: Review & follow-up					*

Note: ** means the most significant relevance, whereas * means significant relevance, yet appropriate considerations are still needed for all dimensions for more effective analyses of standardisation foresight.

Second, a number of interviewees highlighted challenges in defining a concrete typology of certain dimensions of standardisation, due to wide variations and diversities of contexts (in terms of technical domains and institutional cultures) and their standardisation systems (in different countries or even among various SDOs). For example, although 'degree of consensus' is an important factor for deciding '*how*' to standardise, different SDOs develop different types of documents using different terminologies, thus it is difficult to define a common classification system according to their types of deliverables. This actually justifies the use of the roadmap-based framework which is flexible and adaptable, suggesting that individuals or organisations managing the overall process of strategic analyses should adopt, but not be limited to, categories of dimensions proposed in the standardisation mapping framework.

It is to be emphasised that the framework offers only an initial platform for structured discussions, so that appropriate attention is paid to important dimensions to be considered for effective standardisation in support of innovation. Necessary modifications and adjustments are to be made, in order to ensure that it reflects terminologies and conventions that are appropriate for particular technological or institutional contexts of the system being studied. As it is difficult to devise a definite, one-size-fits-all typology that works in all contexts, the current framework and process model have been developed to provide a basic platform without too much specification, allowing flexibility and adaptability for the variety of communities who might use them. Being too general, they thus may not provide sufficiently useful information in some cases, as noted by an interviewee; yet this is in the interest of making sure that there are enough flexibility and scope for scalability for a diversity of cases. Nevertheless, it is still helpful to identify initial basic typology, and future research may involve further elaboration and generalisation of each dimension with more detailed categories for different types of technological and institutional contexts.

Third, a number of interviewees noted that the complexity and variety involved in the framework and process model may reduce their usability. Although they might have found it more difficult to grasp the main principles and features at first glance due to the limited time for interviews, it could also be the case for any processes of strategic planning, particularly ones designed to explore highly complex systems. Participants of such foresight exercises thus need to be given detailed explanations about principles and features of the strategic framework prior to actual analyses, in order to increase their understanding of the framework and expected outcomes. They are also led through the steps by professional facilitators, who provide instructions on detailed activities to be carried out at each stage of strategic processes (Phaal et al. 2010).

Nevertheless, an expert from an SDO highlighted that such educational or instructional activities are particularly important for standardisation foresight activities, because of the high level of complexity and particularity involved even in general processes of standardisation:

> *"It costs a lot of energy in the beginning of standardisation to develop (and educate) the committee of stakeholders… It is generally very difficult for the newbie to get familiar with standardisation processes, because they are so complex… You need to increase the learning curve of experts on process aspects of standardisation."*

Such challenges have also been identified by multiple experts from preliminary interviews and a number of practice literature (e.g., Hatto 2013). It is thus important to inform and educate experts participating in standardisation foresight in the beginning, in order to facilitate overall processes by reducing any potential confusion that may exist due to the complexity involved in standardisation and relevant foresight activities. It is also suggested by an interviewee that appropriate education and training for key persons managing overall processes can help facilitate foresight exercises, by developing their negotiation and conflict-resolution skills required for such collaborative activities.

Fourth, a few interviewees noted issues regarding personalities of participants. Current standardisation and relevant strategic activities are very dependent on individual participants' personalities, just like in many group-based activities; some may be aggressive and assertive, while others are more careful and considerate of others. An expert also highlighted that only a small percentage of participants actually make significant contributions to actual development of standards. This issue may be more significant in interactive and collaborative workshop-based activities of the roadmapping approach, potentially directing standardisation in particular directions in favour of certain entities. In order to mitigate such problems of personalities and maximise benefits for the whole industry, safeguard measures (e.g., facilitation skills of key persons managing the process, better practices of communication, and triangulation with other evidence) may be needed in standardisation foresight analyses. Recognising the psychosocial reality of such roadmap-based activities, a few studies (e.g., Kerr et al. 2012) have also identified rationales for and methods of improving the management and organisation of workshops to alleviate these problems; yet, it is beyond the scope of this thesis, and requires further research.

7.3.3 Implications Regarding Potential Roles of Government

Many interviewees highlighted that because of the nature of standardisation, there are important roles for government or other public agencies in managing the overall process of its strategy development, to support more effective and timely standardisation. Identifying politics between innovation actors as important forces in standardisation dynamics, an interviewee emphasised active roles to be played by government in ensuring that all voices are heard from various stakeholders, supporting fair and unbiased standardisation strategies. Another interviewee also highlighted that due to the distributed nature of standardisation processes, there are potential roles for government or public institutions to overcome the inadequacy of market mechanisms, which alone cannot lead to effective standardisation with the lack of transparency. This is because none of the stakeholders has complete information or direct control over the whole process of standardisation; SDOs manage only administrative processes, whereas different types of stakeholders are involved at different stages of standardisation (Sherif et al. 2005). The issue is becoming even more significant with complex, interdisciplinary technologies, as they involve various SDOs, including ad-hoc organisations (such as consortia), which often emerge and disappear as new issues come and go in standardisation communities, noted another interviewee. Hence, it is also an important role of government or public agencies to perform long-term monitoring of various SDOs, to ensure the effective management of standardisation in complex, interdisciplinary domains.

In addition, there are potential roles for government in encouraging and incentivising various stakeholders to participate in standardisation and relevant foresight activities. Many interviewees noted a lack of participation from the industry (private companies), due to concerns regarding security and trade secrets, as well as a lack of awareness of its importance for their businesses. It is particularly the case in countries with small markets and thus low standardisation capacities, as it would be more efficient for them to adopt existing standards developed by leading countries (in terms of technology and standardisation) with large market power, according to interviewees from Korea. Other interviewees also identified a lack of participation from users, particularly small companies and individuals, mainly because of the lack of financial resources needed to support their travels and education required for participating in standardisation activities. As the lack of balanced representations of stakeholders may result in ineffective standardisation for overall innovation systems, more resources and efforts need to be provided by government, in order to promote sustainable and balanced participation of various stakeholders in standardisation.

7.4 Concluding Remarks

Researchers and practitioners from different backgrounds and perspectives participated in verification interviews, demonstrating the relevance and validity of features incorporated in the framework and process model shown in Chapter 6; as no major changes were needed, they are not replicated in this chapter, but presented in the next chapter. Nevertheless, they provided four particularly useful insights that led to the minor improvement of the framework and process model as well as clarification of their elements, alleviating any potential limitations and additional concerns. These include: the use of specific labels reflecting language used by the community, efforts to identify and engage new stakeholders and SDOs, identifying appropriate categories for vertical and horizontal axes of multiple frameworks at various levels of granularity, and questions to be asked during the review step. Generally agreeing on the usefulness of the framework and process model, the experts also provided insights regarding practicality and utility of using them for systematic and future-oriented analyses of standardisation. Particular attention was given to issues such as cross-referencing between the framework and the process model for effective presentation, flexibility and adaptability in a diversity of contexts, the need for educating and instructing participants in foresight analyses, and potential roles of government to engage and support various stakeholders.

8. DISCUSSION AND CONCLUSION

This thesis was set out to develop a systematic and practical tool for exploring complex and dynamic interplays between standardisation and technological innovation, which can be used to support timely and effective standardisation. Challenges were identified in such systematic and future-oriented analyses, due to high levels of complexity and variety involved in interactions between standardisation and other aspects of innovation. This thesis thus sought to answer the research question of "*how might complex dynamic interplays between standardisation and technological innovation be analysed systematically, and subsequently accounted for in strategic policy foresight?"*

Drawing on results and discussion presented in previous sections, this chapter summarises the key findings and overarching discussion of the research, in the context of answering the above question and associated sub-questions. It then discusses how the current thesis provides contributions to advance our knowledge, and valuable practical implications for standardisation in support of technological innovation, particularly appropriate role of government and public agencies. Finally, limitations of the current research are discussed, providing guidance and directions for future research.

8.1 Summary of Key Findings

The key findings of the research are as follows, each answering each of five sub-questions presented in section 1.3:

- A systems perspective on standardisation helps analyse its various roles in technological innovation, particularly its mediating role in supporting functions of innovation systems (discussed in section 8.1.1).

- Unifying existing models, a novel standardisation mapping framework is developed by integrating important dimensions of standardisation – i.e., issues of ‘*what*’, ‘*why*’, ‘*when*’, ‘*how*’, and ‘*who*’ – on a holistic framework of strategic roadmap (discussed in section 8.1.2). Enabling systematic, multi-dimensional analyses of standardisation with focus on technological complexities, the framework provides more comprehensive understanding of its dynamic interplays with innovation (discussed in section 8.1.3).
- This roadmap-based framework can also be used as a policy tool for standardisation foresight, assisting timely and effective standardisation in support of technological innovation (discussed in section 8.1.4).
- A structured process model for using the framework for standardisation foresight is developed, addressing challenges with managing and organising such future-oriented analyses in complex, multidisciplinary technological systems (discussed in section 8.1.5).
- Increasing roles need to be played by government and public agencies as coordinator, supporter, and educator, for timely and effective standardisation of complex technological systems (discussed in section 8.1.6).

8.1.1 Standardisation as Mediating Functions of Innovation Systems

Taking a systems perspective on standardisation in the context of technological innovation, the current research highlights its complex and dynamic nature, interacting with various other aspects of innovation. As they are highly interdependent on each other, a more holistic approach is needed for comprehensive understanding of roles of standardisation in broader contexts of innovation. In order to overcome limitations of existing literature that present only fragmented views on standardisation, a systematic and dynamic perspective of the innovation systems functions approach is adopted. It allows us to observe that standardisation plays diverse functions to support a variety of innovation activities, including legitimation, influence on the direction of search, development of positive externalities, creation and transfer of new knowledge, and entrepreneurial experimentation (see section 2.2 for details).

Such systems perspective also highlights ‘mediating’ roles of standardisation in supporting these various functions of innovation systems. It is widely recognised that standardisation plays important roles of knowledge transfer and diffusion through final documents of standards publications, as well as collaborative learning activities of developing standards. By transferring knowledge between a variety of innovation actors, it also links their innovation activities and functions, facilitating interactions and interplays between them. This, in turn, enhances the overall functional dynamics of innovation systems, expediting innovation processes and promoting further innovation. Hence, standardisation supports innovation by not only assisting knowledge diffusion, but also strengthening overall dynamics of systems through 'mediation' of diverse activities across various elements and stages of innovation systems. Although the linkage provided by standardisation through knowledge diffusion is somewhat implied in the framework developed by Tassey (2000), it does not take further implications to its roles in 'mediating' innovation activities and functions; this could be done by adopting more holistic and systematic perspectives on standardisation.

This 'mediating' role of standardisation is expected to become more important in modern technologies with complex, interdisciplinary, and systems-like nature. Many interviewees throughout the research identified the act of standardisation as an important forum, where stakeholders with diverse backgrounds and perspectives share knowledge gained from their innovation activities. Published documents of standardisation also facilitate such activities by providing common language and essential platform on which multidisciplinary technical discussions and collaborations can occur. They may lead to further innovation and development, by producing aggregated expertise and improved knowledge, and by raising awareness of important issues where collaborative efforts are needed, as observed in various case studies. These are particularly useful in complex heterogeneous technologies, where interactions between various organisations and disciplines are critical for knowledge development and diffusion, thus the overall functioning of innovation systems. As shown from the case study of PV technology, collaboration between researchers and companies may also provide effective linkages between R&D and industry – which are becoming increasingly challenging as experts tend to focus on specific areas of technical expertise –, promoting the development of new industry based on scientific R&D.

8.1.2 Standardisation Mapping Framework with Unified Dimensions of Standardisation

Although the innovation systems functions approach provides holistic and dynamic perspectives of complex interplays between standardisation and technological innovation, its high level of abstraction limits their systematic and comprehensive understanding with a detailed level of analysis. In order to disaggregate complexities and variations associated with their dynamics, a systematic and coherent list of dimensions has been developed, by integrating various elements and factors characterising standardisation in the context of technological innovation. Incorporating important issues addressed in existing models and other strategic considerations identified from multiple case studies, five dimensions are identified, including: '*what*' technology and innovation elements are relevant to standardisation, '*why*' standardisation is needed, '*when*' and '*how*' to standardise, and '*who*' is involved in standardisation (see Table A.4 in Appendix D for details). Given increased challenges with complex technological systems, particular emphasis is placed on technological elements associated with standardisation.

Capturing this information on a holistic and integrative framework of general strategic roadmap developed by Phaal & Muller (2009), a novel standardisation mapping framework has been developed (shown in Figure 8.1). The framework highlights 'mediating' functions of standardisation (by illustrating them as linkages instead of layers), as well as its multi-dimensional nature in a coherent and systematic way, with focus on technological complexities. Thus offering unified and long-term perspectives than existing models (discussed in section 2.3), it is useful for more comprehensive and systematic analyses of standardisation in broader contexts of technological innovation, as demonstrated in case studies in Chapters 4 and 6. Verification interviews have also confirmed the relative completeness and stability of the framework (as shown in Figure 3.3 in section 3.6.2), suggesting that no further development is needed within the scope of the current thesis.

Although its sub-categories need to be adapted and modified to reflect the language and terminology used by a particular community using the framework, the framework presents an initial platform to begin structured discussions for such systematic analyses, adopting general categories that are conventional and commonly used in broader contexts. Case studies and verification interviews also suggest that such an integrative and systematic approach is potentially more valuable, as many technological systems are becoming interdisciplinary and convergent, resulting in increased interactions and complexities associated with dynamics between standardisation and innovation.

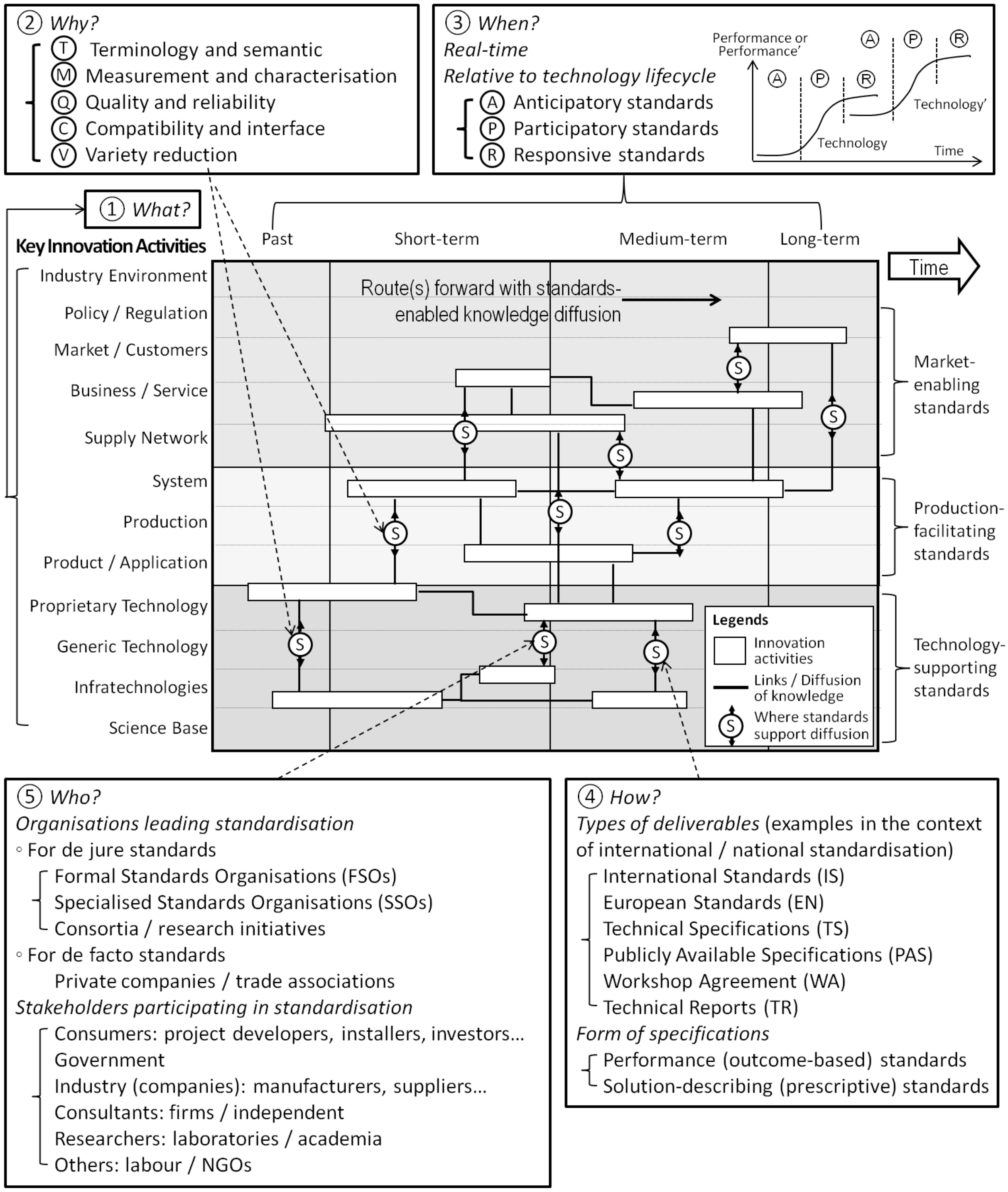


Figure 8.1 Final standardisation mapping framework (replicated from Figure 6.7)

8.1.3 Systematic Analyses of Standardisation in Technological Innovation

Although it is not an all-encompassing model explaining every possible interaction between standardisation and innovation at a micro level, the standardisation mapping framework is a flexible and adaptable framework highlighting key categories of their potential interplays by drawing attention to important dimensions of standardisation. It has thus been used for systematic analyses of standardisation for the case of PV technology (presented in Chapter 6), providing greater insights into complex and dynamic interplays between standardisation and other aspects of technological innovation. Interesting trends and patterns have been observed on how various dimensions of standardisation evolve across different phases of innovation, reflecting changes in complex technological systems; these are discussed below.

- Standards associated with different elements of technology and innovation activities have been developed across different stages of the innovation journey: mainly technology-supporting standards in early stages where basic scientific research dominated, followed by production-facilitating standards and market-enabling standards as systems develop and markets expand.
- Although not definitive, there is a general trend that standards with particular roles and functions dominate certain stages of the innovation journey. Measurement and testing standards emerge in early technological innovation; quality and reliability standards are later developed as products and applications are introduced; and compatibility and interface standards tend to appear with the widespread deployment of larger systems. Possibly due to the increasing complexity of technologies and systems that are interrelated to each other, it has been also observed throughout the research that many recently developed standards tend to play more than one function at once.
- The timing of standards is closely related to intrinsic capabilities of particular technology that standards are associated with: anticipatory standards mainly at the beginning of new technology, and responsive standards after some market success. Such relations repeatedly occur across multiple technology lifecycles for different levels of systems complexity (see section 6.2.2 for detail).
- For emerging areas of technology, technical reports are often generated as a result of workshops among researchers; existing standards from analogous technologies are sometimes also adopted and reused, as their technical contents and experiences can significantly accelerate the development of new standards because of technological commonalities (Bergholz et al. 2006). As technology progresses, more formal standards with high levels of consensus, such as national and international standards, tend to be

developed by a wider group of participants, including manufacturers, materials / equipment suppliers, and systems-related stakeholders.

8.1.4 Using the Framework as a Policy Tool for Standardisation Foresight

The standardisation mapping framework can be also used by policymakers and standards organisations as a practical tool for standardisation foresight. Readily adaptable within general policy foresight for technology and innovation, the framework can be used to identify policy needs for standards-related issues, including areas that require funding for standardisation and relevant R&D, by identifying potential gaps or barriers. In addition, systematic and holistic perspectives of the framework – with focus on technology elements relevant to standardisation – can be useful for anticipating specific standardisation needs and developing relevant strategies in particular technological systems. It is facilitated by illustrating standardisation as linkages between innovation activities and functions, rather than a single layer, as represented in previous roadmap-based frameworks (e.g., Phaal & Muller 2009; Phaal et al. 2010). Such anticipatory analyses are becoming more critical for timely and effective standardisation, as reactive approaches are no longer competitive due to the fast pace of technological development, as discussed in section 2.4.3.

The consensus-based nature of strategic roadmapping is also useful for such foresight analyses of standardisation, where bringing consensus and creating a common vision among various stakeholders with different interests is particularly important. By structuring various perspectives of innovation in a layered form, the framework helps gathering information from, and building consensus among, a variety of stakeholders who make different contributions to standardisation. It thus provides a collaborative platform where various experts are brought together to develop coherent strategies for standardisation and other relevant issues (such as intellectual properties and regulations). Nevertheless, it is important to take appropriate actions to mitigate potential problems regarding psychosocial issues that are inherent in such group-based activities, as discussed in section 7.3.2.

Multiple case studies highlight that such collaborative efforts among experts from different backgrounds and disciplines are becoming more important, in order to meet increasing demands for standardisation in highly complex and interdisciplinary technologies. More standards developed by different groups are being interrelated with each other, requiring the alignment and coordination of standardisation activities carried out by various groups with different interests. In particular, standards developed by various SDOs are becoming increasingly related to each other, calling for close collaboration and coordination between them. By adopting more holistic perspectives, the roadmap-based framework is expected to enable identification of such interactions and linkages, helping manage diverse standardisation activities in a more coherent and harmonised way. In addition, the flexibility and scalability of the framework – as demonstrated from the in-depth case study, where particular perspectives in certain periods of time are zoomed in – can also support the collaboration of multiple standardisation groups. For example, detailed mapping frameworks for individual technological domains developed by different SDOs or WGs can be collated and integrated into a broader framework of a multidisciplinary industry (see section 7.2.2 for detailed discussion on issues of dissemination and synthesis of multiple frameworks at various levels of granularity).

8.1.5 Process Model for Strategic Standardisation Foresight

Despite the potential of the standardisation mapping framework as a foresight tool in complex technological systems, additional challenges exist because of intrinsic limitations of the roadmap-based framework in addressing issues outside the system under consideration. A more systematic and structured process is needed, in order to address challenges associated with organisation, management, and governance of foresight exercises involving multi-stakeholders with multi-perspectives. The process model for using the framework for standardisation foresight has thus been developed through the review of existing literature as well as case studies (shown in Figure 8.2, and see Table A.5 in Appendix D for sources of evidence). The actual process would be more complex and iterative, yet it offers an initial platform to plan for such analyses, providing a structured and rational view based on systems and process thinking.

Detailed procedures of each step of the process model would differ depending on the purpose of strategic analyses. Nevertheless, multiple case studies of existing roadmapping exercises (presented in Chapter 5) and verification interviews demonstrated potential value of the following tools and activities in managing complexities and uncertainties associated with standardisation of complex, multidisciplinary technologies:

- Gathering existing information (from both previous analyses and preliminary insights of participants) for increased efficiency in design and organisation of foresight analyses;
- Identifying an appropriate mix of various stakeholders with a balanced perspective of innovation systems;
- Establishing common definitions of fundamental concepts and developing system architectures (i.e., high-level visual conceptualisation of the overall system) at an early stage; and
- Structured methods of anticipating the future (such as use case analyses), effectively managing high levels of complexity and uncertainty associated with innovation, particularly in emerging technologies where markets and user requirements are less articulated.

Inspired from verification interviews, Figure 8.3 has been also developed, mapping detailed activities of each step in the process model against relevant dimensions of standardisation (and their sub-categories) to be considered during each activity. By providing linkages between the framework and the process model, it is expected to provide useful guidance for practitioners who actually use them for standardisation foresight.

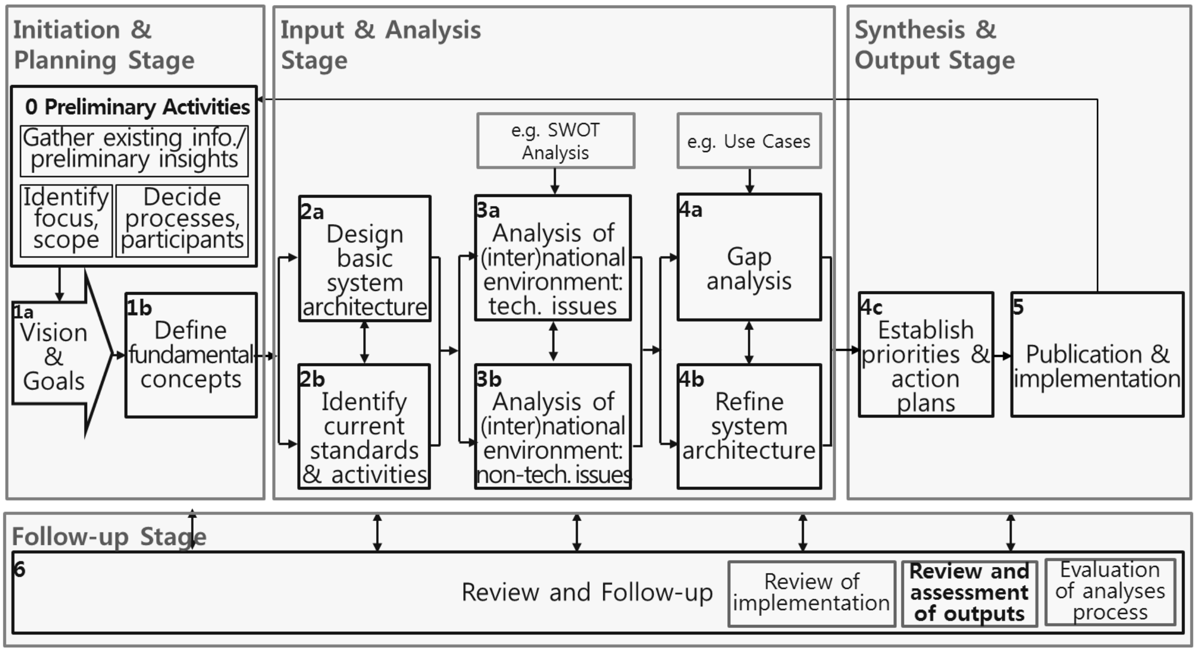


Figure 8.2 Final process model for using the framework for standardisation foresight (with major changes based on verification interviews highlighted in bold)

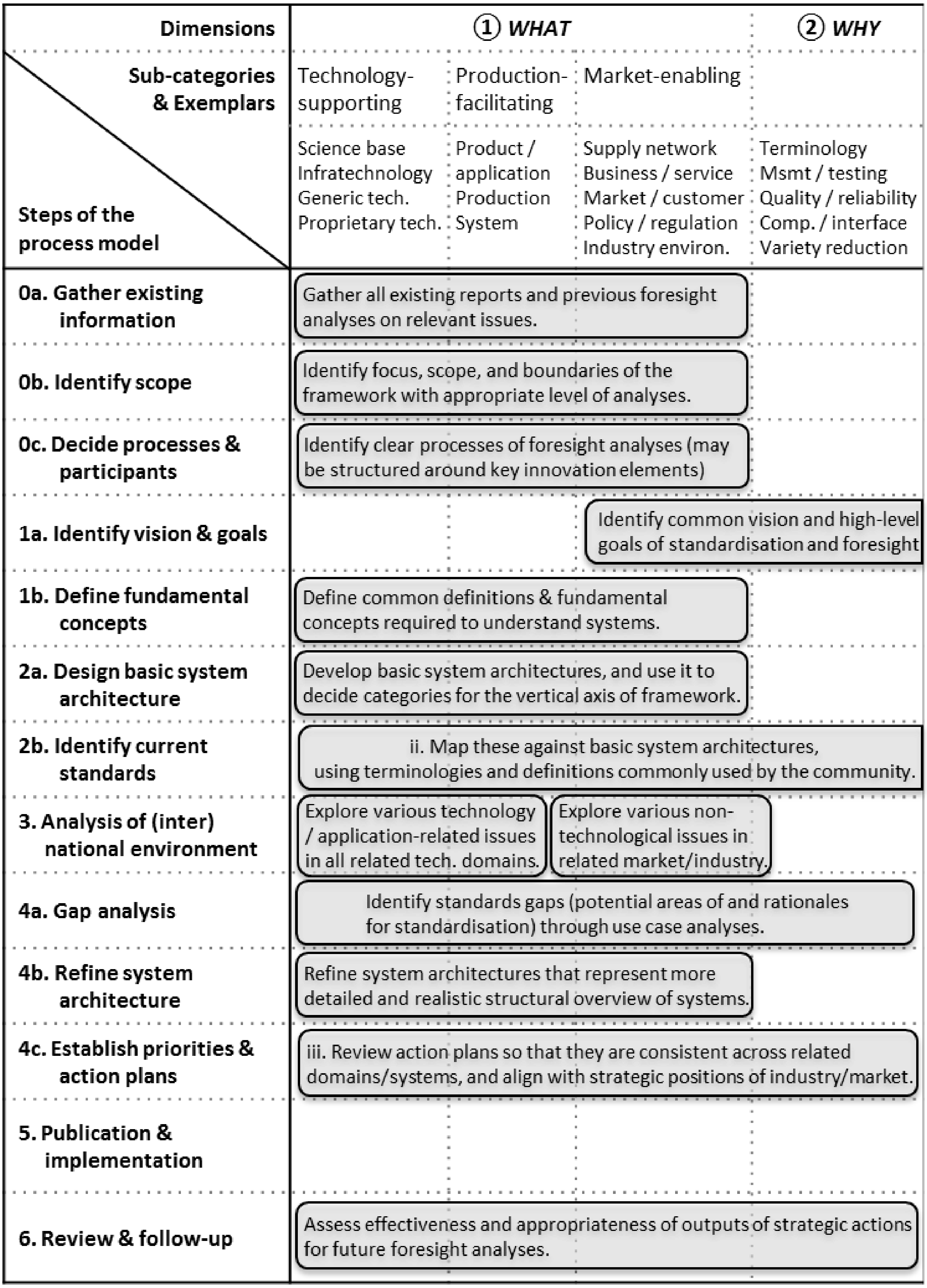


Figure 8.3 Detailed activities of steps included in the process model

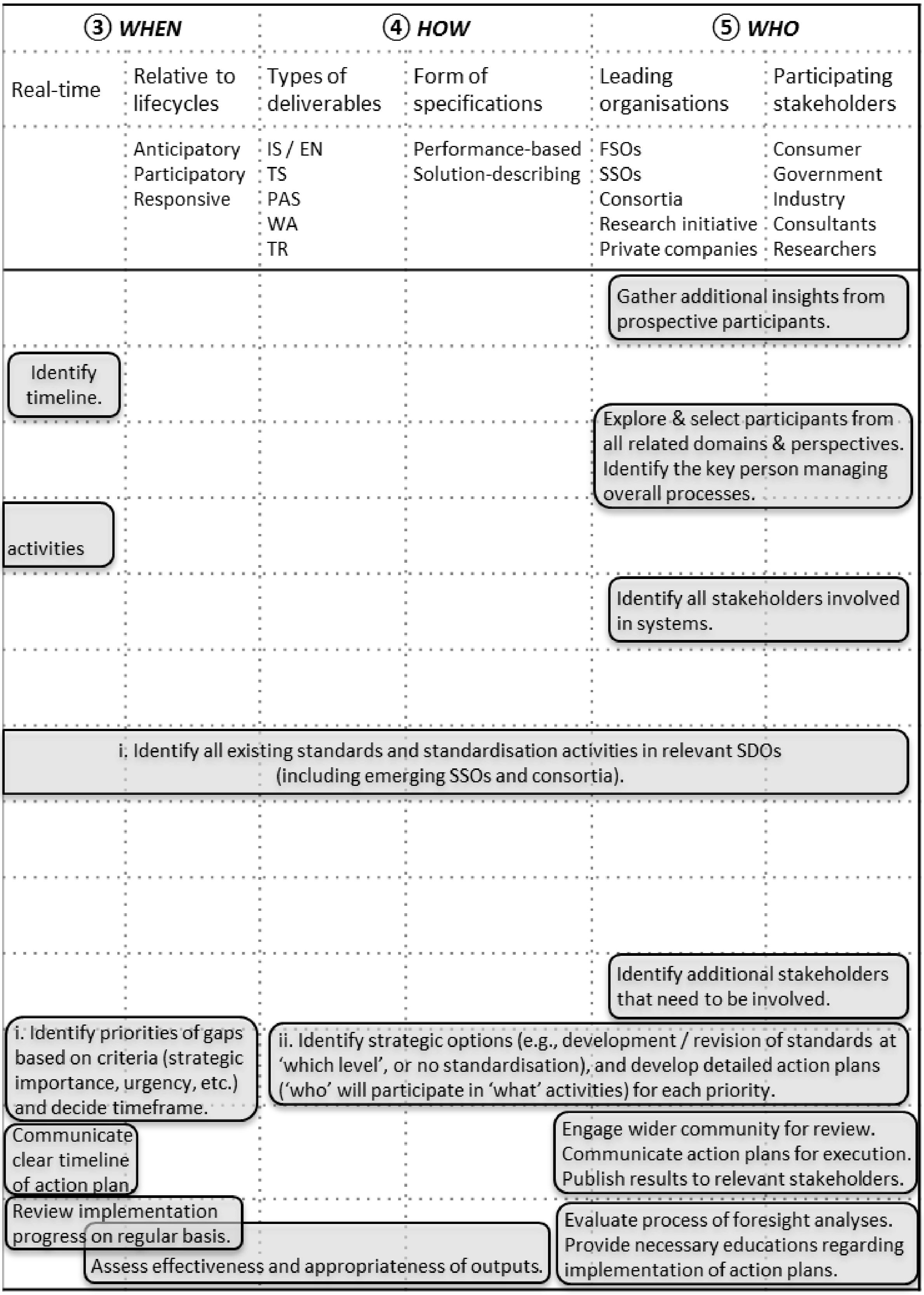


Figure 8.3 Detailed activities of steps included in the process model (continued)

8.1.6 Roles of Government and Public Agencies in Standardisation Foresight

In contrast to existing literature and prevailing perceptions in practice that there should be only limited public intervention in standardisation (as discussed in section 2.4.1), the findings of this thesis provides rationales for increasing roles of government and other public organisations in standardisation and relevant foresight activities, particularly as convenor/coordinator, supporter, and educator; these are discussed in this section.

Convening and coordinating various stakeholders and SDOs

The increasing role of government and public agencies is mainly due to the growing number of stakeholders – including multiple government departments and agencies – involved in standardisation of complex technological systems. As traditional sector-specific and market-driven system of standardisation is no longer responsive to their complex dynamics, government needs to play the role of 'honest broker', supporting collaborate efforts of a broad cross-section of stakeholders. These collaboration and coordination are important to avoid negative impacts of standardisation due to competition, duplicative efforts, or incompatible (sometimes even conflicting) standards among various SDOs, as identified from various case studies. In addition, challenges with the lack of transparency – due to the distributed nature of managing standardisation – increase in such interdisciplinary areas, calling for active roles of government in managing the overall strategic process to ensure effective standardisation (see section 7.3.3 for details). In particular, standardisation activities in complex system-like areas enabled by ICT are often carried out by consortia with short lifecycles; the role of government or other public agencies is thus more important for long-term, sustainable management of standardisation activities.

Supporting standardisation in areas of national or societal importance

Although the convening or coordinating role can be also conducted by other public organisations, there are other rationales for government support in standardisation and its strategic foresight, particularly in areas of national economic or societal importance. Case studies discussed in Chapter 5 show that government may be interested in driving initiatives for standardisation foresight, in areas where standardisation serves as critical national infrastructure that is often under produced due to its public good nature (e.g., energy, security, and transport). A number of experts and literature also highlight needs for government's engagement in standardisation of key areas with public and societal policy objectives, including consumer safety, environmental protection, and health and safety issues (Libicki et al. 2000; EXPRESS 2010). In order to avoid potential system failures in such quasi-public good resources (as discussed in section 2.4.1), government needs to take more coherent, systematic, and long-term perspectives, ensuring that appropriate levels of resources and efforts are provided for relevant standardisation and foresight activities. This is particularly important in countries where standardisation is generally driven by the private sector, as their SDOs (e.g., ASTM and BSI, both of which are companies) tend to focus on generating economic benefits, as shown from both the PV case study and verification interviews. The issue of different approaches to standardisation adopted in different countries are further discussed below.

Different strategic approaches by different governments

Adopting different approaches, different governments play different roles in standardisation and its strategic foresight. Expert views from verification interviews highlight that national FSOs – such as BSI and DIN – tend to take bottom-up approaches focusing on technology perspectives, whereas regional or international FSOs – such as CEN/CENELEC and ISO – take top-down approaches focusing on policy and regulation perspectives (as discussed in section 7.2.2). Other interviewees as well as case studies in Chapter 5 demonstrate that even national FSOs, especially ones from countries with less experience in standardisation such as Korea and China, may take more top-down approaches driven by government. As they are likely to face higher costs of developing and disseminating standards, it would be more effective for those countries to focus limited resources and efforts on specific areas with high potential of competitive advantages. On the other hand, case studies show that countries with leading capabilities in terms of technology and standardisation – such as US and Germany – take more bottom-up approaches driven by the industry to standardisation and its foresight analyses.

Such differences in strategic approaches between leaders and followers, as well as governments at different levels, are due to different needs and institutional systems associated with standardisation, as demonstrated from case studies in Chapter 5. Appropriate strategic approaches need to be taken depending on contexts, taking into account of various factors, including strategic positions of the industry and purposes of standardisation foresight. It appears that the roadmap-based framework can be adapted to both approaches, or even combinations of the two, by providing holistic and integrative perspectives of overall systems without losing detail and clarity. In fact, Ernst (2009) claims that a combination of pragmatic and flexible bottom-up approaches with systematic and strategic top-down approaches would be useful for standardisation in the future, as either approaches alone no longer seem to provide effective solutions. It is beyond the scope of this thesis to explore this issue in greater detail, but would be an interesting area for further research.

Providing education and training for effective standardisation

This research has identified another important role for government and public agencies to provide appropriate education regarding standardisation, engaging a wider community in standardisation and relevant foresight activities. Case studies have shown that the lack of participation of a variety of innovation actors, particularly from the industry, is due to not only limited resources, but also lack of understanding on the importance of standardisation for their businesses. Public education is thus needed to increase understanding of, and encourage their participation in, standardisation and relevant strategic activities. This might be particularly important for countries in the transition period from follower to leader in terms of standardisation capabilities, as the bottom-up approach requires more active participation from the industry than the government-centric top-down approach, as noted by various experts from both case studies and verification interviews.

Case studies and verification interviews have demonstrated that education is also important for recruiting new human resources in standardisation activities. As innovations from new technologies continuously – and increasingly – emerge to be integrated in complex, high-level systems, experts from these areas also need to be invited for effective standardisation and relevant strategic activities. However, due to high levels of complexity and particularity associated with standardisation-related activities, many standards organisations across the world find it difficult to recruit new members from outside their existing networks. This increases challenges with anticipating appropriate standardisation needs in a timely manner, responding to rapid development of new technologies and markets. Therefore, government needs to provide necessary education and trainings for the wider community – who may provide important perspectives in the future –, to ensure that appropriate participants are continually identified and invited to standardisation and relevant foresight activities.

8.2 Contributions and Implications of the Research

This section discusses implications of the findings of this thesis, for theory, practice, and research methodology.

8.2.1 Contributions to Theory

The findings provide three particularly important theoretical implications regarding standardisation in the context of technological innovation. They complement existing theories, providing greater understanding and advancing our knowledge of standardisation and innovation.

A holistic and integrative approach to standardisation, highlighting its 'mediating' roles

The main theoretical contribution of this research is providing a systematic, holistic, and integrative perspective on standardisation in the context of technological innovation. As discussed in section 2.1.4, existing literature on standardisation are fragmented and limited, taking different perspectives from particular domains and disciplines. By adopting a systematic and dynamic approach of the innovation systems functions, the thesis provides more comprehensive and long-term perspectives of how standardisation actually supports technological innovation in broader contexts.

It particularly highlights the 'mediating' role of standardisation in supporting overall functional dynamics of innovation systems, by transferring new knowledge between varieties of actors and thus linking their innovation activities. Standardisation as channels of knowledge diffusion – through both published documents and act of standardisation – and its role as linkages have been partially discussed in previous academic and practice literature (e.g., Tassey 2000). By taking a more holistic and integrative perspective, this thesis has taken its implications further, identifying 'mediating' roles of standardisation by facilitating constant interactions and interplays across various activities and functions of innovation systems.

Unifying framework for standardisation in technological innovation

Disaggregating complexities and variations associated with standardisation in the context of technological innovation, the current thesis provides a more systematic and coherent list of important dimensions of standardisation. It incorporates various aspects identified in existing literature that are critical in understanding dynamics between standardisation and innovation (i.e., issues of '*what*', '*why*', and '*when*'), as well as additional strategic considerations that have been often neglected in academic literature (i.e., issues of '*how*' and '*who*'). Thus providing more detailed characterisation and clear articulation of dimensions of standardisation, particular emphasis is placed on technology-related issues, given their importance and urgency in complex systems of modern technologies.

By capturing this information with a holistic and integrative approach of strategic roadmap, standardisation mapping framework is developed, unifying existing models that address only certain aspects of standardisation with different lifecycles (e.g., Tassey 2000; Sherif 2001; Blind & Gauch 2009). Thus providing systematic, comprehensive, and long-term perspectives of standardisation in the context of technological innovation, the framework allows more precise and complete analyses of their dynamics. Case studies presented in Chapters 4 and 6 demonstrate the value of the framework for such multi-dimensional analyses of complex and dynamic interplays between standardisation and technological innovation over extended periods.

The case studies also provide greater understanding of these dynamics and interactions, complementing existing frameworks developed previously. In particular, relations between the timing of standards (relative to technology lifecycle) and intrinsic capabilities of technology has been identified across multiple technology lifecycles for different levels of systems complexity, as opposed to a single lifecycle for the entire innovation journey as suggested by Sherif (2001) (see section 6.2.2 for details).

Process model for foresight analyses at a systems level

By incorporating effective tools and activities adopted in existing practices (see section 8.1.5 for details), the process model developed in this research presents more advanced processes than existing studies (e.g., Phaal et al. 2010) for roadmap-based foresight exercises at a policy level. It thus contributes to the limited academic literature that supports the theoretical underpinning of strategic roadmapping, particularly those with a high-level systems perspective.

8.2.2 Implications for Practice

The findings can draw two particularly useful practical implications, which are discussed in this section.

Strategic policy tool for standardisation foresight

The main practical implication of this thesis is providing a framework and a process model that standards organisations and relevant policymakers can use for systematic foresight for standardisation in support of technological innovation. Many practitioners have identified needs for such strategic tools to support both general policy foresight with standards-related issues and more specific standardisation foresight in particular technological systems (see section 2.4.3). Verification interviews substantiate the potential practicality and usefulness of the framework and process model developed in this research, as discussed in section 7.3.1.

Although the proposed process model mainly focuses on issues relevant to standardisation, some of the tools and activities introduced in the process model can be also useful in other similar foresight analyses at a public policy level. For example, preliminary activities to gather existing information and developing systems architectures may increase efficiency in design and organisation of foresight exercises, particularly in complex technological systems where there are various stakeholders involved from different organisations and disciplines. This thesis thus provides more effective and useful guidelines for roadmapping and other foresight practices at a systems level with long-term perspectives.

Standardisation as indicators of technological paradigms: using the standardisation mapping framework to inform innovation strategies

As discussed in section 6.4.1, the standardisation mapping framework can also be used for general innovation strategy development by providing greater insights into the dynamics of innovation systems, since standardisation may be useful indicators of changes in technological 'paradigms' (Metcalfe & Miles 1994). As standardisation reflects changes in technological systems, key characteristics and patterns of standardisation activities –

especially when considered in an integrative way – may be used as indicators of particular phases of the technology development and innovation journey. Such information can inform policymakers and other business managers to make appropriate reviews or strategic decisions in a timely manner, and also guide how various actors should coordinate with each other, supporting innovation more effectively.

8.2.3 Lessons (Learning Points) for Research Methodology

The current research also provides lessons for research methodology, particularly regarding the visual mapping process adopted to collect and analyse data for the in-depth case study of PV technology (see section 3.5.1 for details). Despite its low level of maturity as an established research method, there were significant advantages of using the technique that is compatible with the proposed roadmap-based framework. It was effective for gathering interviewees' hidden insights regarding dynamics and possible causal relationships between various activities of complex innovation systems. It also helped organising, analysing, and validating their narratives in a more structured and systematic way. In order to facilitate the process of data collection during expert interviews, a pre-populated map was developed using secondary sources, to capture plentiful insights in limited times, and to stimulate interviewees' thinking of their past experiences within a broader context of overall innovation systems.

Despite such advantages, there were also some limitations; it heavily depended on active participation of interviewees and their understanding of the process. Some interviewees were hesitant to record their recollections on the map, or preferred to answer specific questions rather than generating their own narratives from their perspectives, possibly due to the lack of familiarity with the technique. A few interviewees also preferred to tell own monologues on their experiences and perspectives, rather than being confined to the given structure of the map provided. Due to such limitations, this technique was used as a supplementary method to support data collection during expert interviews. Such challenges need to be addressed, for the visual mapping technique to be used as a more reliable and valid method on its own.

8.3 Limitations and Areas for Future Research

8.3.1 Limitations and Further Areas for Research

Despite the rigorous research design and measures to ensure the quality of outputs (as discussed in Chapter 3), the findings are not without limitations due to time and resource constraints of the PhD study. This section discusses the limitations, along with suggestions for future research to address them.

Limited generalisability of the findings

Although the value of the proposed framework and process model in systematic and future-oriented analyses of standardisation has been substantiated, their generalisability has not been demonstrated, because of the limited number of case studies conducted. This is, of course, beyond the scope of the current thesis, and an obvious area for future research would be investigating the applicability of the framework and process model in wider technological domains and systems. Using the framework for historical analyses of standardisation dynamics in a variety of innovation contexts – such as different domains and regions – can further substantiate the findings, potentially leading to improvements, or even typological refinements of the framework in specific contexts. Conducting action-based research of using the framework for standardisation foresight in various real-life settings may also identify further modifications necessary to the framework and process model, leading to more generalisable findings of the research. This could also provide more comprehensive understanding of standardisation in the context of innovation, such as categories of variation and selection, as identified in existing literature adopting evolutionary perspectives (e.g., Metcalfe & Miles 1994).

Limitations in scope of the research

Given challenges in standardisation of complex technological systems, the scope of this thesis is limited to technology-related elements of innovation, yet innovations come in many different forms, including service and business model innovations. Expanding the scope of the research to such a wide variety of innovation types may enrich our understanding of standardisation in the context of innovation, and also provide useful implications for systematic and future-oriented analyses of standardisation in various contexts. It may also be possible to develop a typology of the framework and process model for different types of innovations; Egyedi & Sherif (2010) discuss how different categories of innovation – i.e., incremental, architectural, platform, and radical – have different impacts on standardisation, thus requiring different strategies and roles of government. It would be interesting to explore how issues of various types of innovations can be linked to or integrated with the framework and process model developed in this research.

8.3.2 Other Areas for Future Research

This section discusses three additional areas for future research that have been identified throughout this research, regarding standardisation in the context of technological innovation.

Detailed categorisation of sub-categories

Although key dimensions of standardisation and their exemplar sub-categories are identified throughout the research, it is beyond the scope of this thesis to explore them in a greater level of detail; more research is thus needed on further classification and characterisation of these dimensions and their sub-categories. For example, detailed categorisation for various stages of standardisation lifecycles (such as requirements elicitation, development of base standard, and profiling) may help develop more thorough action plans. It is also discussed in section 7.2.1 that further categorisation is needed for different types of stakeholders (and SDOs) involved in standardisation, according to their interests and roles (including creators, implementers, users, and self interested parties). There may be value in creating a systems architecture-like diagram for actor systems based on this information, to support more systematic identification of stakeholders to be involved in standardisation and relevant foresight exercises, ensuring a balanced representation of the system being studied; further exploration is needed in the future.

Needs for more effective regional and international standardisation systems

With increasing globalisation, case studies and verification interviews suggest that there are growing needs for international or regional standardisation among countries who share similar contexts in terms of economies and markets. However, there are significant challenges due to bureaucratic processes and different national institutional systems, as current standardisation systems are more country-specific (see section 6.4.2 for details). The increasing emergence of consortia and research initiatives involving various stakeholders across the world may be in response to such issues, yet there remain further challenges regarding competing advantages over national competitiveness. Many experts thus suggest that new practices of collaboration and coordination among different countries are needed to achieve more effective international or regional standardisation in the globalised world; there may be opportunities in adopting the consensus-based roadmapping approach developed in the current thesis, which need to be explored in the future.

Modularisation and standardisation

It has been identified during the verification study that 'modularisation' of technological systems would be particularly effective in addressing increased challenges associated with standardisation of complex technologies that are interdisciplinary, systems-like, and fast-evolving. Such technological systems consist of various devices and sub-systems with different technological bases, thus involving a variety of stakeholders with different backgrounds. In order to ensure compatibility between them while encouraging small individual innovations within each device and sub-system, these systems need to be modularised according to functions, and supported by standards at the interfaces between these modules, noted multiple interviewees. These issues need to be explored in future research.

8.4 Concluding Remarks

Building on the innovation systems approach, this thesis provides a systematic and integrative perspective on standardisation in the context of technological innovation. Highlighting 'mediating' roles of standardisation in supporting various activities and functions of innovation systems, it provides more comprehensive understanding of their complex and dynamic interplays. In order to explore these dynamics with a more detailed level of analysis, key dimensions of standardisation – i.e., issues of '*what*', '*why*', '*when*', '*how*', and '*who*' – have been identified, with particular focus on technological complexities.

By integrating them with a holistic approach of strategic roadmapping, a novel standardisation mapping framework is developed. Unifying existing models that represent only partial pictures of standardisation, it enables systematic, multi-dimensional analyses of evolving roles of standardisation in supporting technological innovation. The framework can also be a useful practical tool for anticipating future standardisation needs and developing relevant strategies, due to the function of the roadmapping approach as a strategic foresight tool based on consensus-building. A structured process model for using the framework is developed, in order to address challenges with managing and organising such future-oriented analyses for standardisation in complex, multidisciplinary technological systems. Roles of government and other public agencies as convenor/coordinator, supporter, and educator are also found to be critical for effective standardisation and relevant foresight exercises. Findings of this thesis are expected to help standards organisations and policymakers make more informed decisions for timely and effective standardisation in support of technological innovation, and to broaden the research field of standardisation by providing a more systematic perspective.

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APPENDICES

Appendix A – Profiles of Interviewees

Table A.1 Profiles of experts engaged in the practice review

Study Type	Expert #	Organisation*	Nationality	Experience / Perspective in Standardisation	Note
Participant Observation**	1	BSI	UK	Strategic management in national SDO	
	2	DIN	Germany	Strategic management in national SDO	
	3	AFNOR	France	Strategic management in national SDO	
	4	European Commission	Netherlands	Strategic management in international SDO	
Preliminary Interviews	5	BIS	UK	Strategic management in government agency	Via phone
	6	KATS	Korea	Strategic management in government agency	2 interviews
	7	KATS	Korea	Strategic management in government agency	2 interviews
	8	KATS	Korea	Strategic management in government agency	
	9	KSA	Korea	Strategic management in national SDO	
	10	TTA	Korea	Strategic management in national SDO	2 interviews
	11	ETRI	Korea	Participation as researcher from laboratory	
	12	Kyunghee University	Korea	Participation as academic	Focus-group
	13	Kyunghee University	Korea	Participation as academic	Focus-group
	14	KATS	Korea	Strategic management in government agency	
	15	KATS	Korea	Strategic management in government agency	
	16	KRISS	Korea	Strategic management in government agency	Focus-group
	17	KRISS	Korea	Strategic management in government agency	Focus-group
	18	NIST	US	Strategic management in government agency	

19	NIST	US	Research in standardisation	
20	NIST	US	Strategic management in government agency	Focus-group
21	NIST	US	Strategic management in government agency	Focus-group
22	NIST	US	Strategic management in government agency	Focus-group
23	NIST	US	Strategic management in government agency	2 interviews
24	NIST	US	Strategic management in government agency	
25	ANSI	US	Strategic management in national SDO	Via phone
26	KSA	Korea	Strategic management in national SDO	
27	ETRI	Korea	Participation as researcher from laboratory	
28	IIEEJ	Japan	Participation as researcher from laboratory	
29	Korea University	Korea	Academic research in standardisation, Participation as academic	
30	Erasmus University	Netherlands	Academic research in standardisation	
31	Technical University Berlin	Germany	Academic research in standardisation	
32	ASTM	China	Strategic management in international SDO	
33	Diponengoro University	Indonesia	Academic research in standardisation	
34	KSA	Korea	Strategic management in national SDO	

* Note: See page xvi for definitions of the abbreviations.

** Note: Participant observation study was carried out, by attending the ‘Standardisation Tripartite Workshop’ where a group of standardisation experts from Europe gathered to discuss and share lessons or practices looking into a more systematic approach to standardisation activities.

Table A.2 Profiles of interviewees in case studies of existing standardisation roadmapping exercises

Case	Expert #	Organisation*	Experience / Perspective in Standardisation Roadmapping Exercises	Note
Case 4: ICT Standardisation Strategy Map (TTA 2013)	1	TTA	Administration of overall roadmapping processes	
	2	ETRI	Participation as researcher from laboratory	
	3	ETRI	Participation as researcher from laboratory	
	4	ETRI	Participation as researcher from laboratory	
	5	ETRI	Participation as researcher from laboratory	
	6	ETRI	Participation as researcher from laboratory	
	7	ETRI	Participation as researcher from laboratory	
	8	ETRI	Participation as researcher from laboratory	
	9	ETRI	Participation as researcher from laboratory	
	10	NIA	Participation from government agency	
	11	KARUS	Participation as a member of trade association	
	12	Microsoft Korea	Participation from industry	
	13	SK Telecom	Participation from industry	
	14	Samsung Electronics	Participation from industry	
	15	Samsung Electronics	Participation from industry	
	16	SK C&C	Participation from industry	
	17	University of Seoul	Participation as researcher from academia	Via e-mail
	18	Ewha Womans University	Participation as researcher from academia	
	19	Korea Cyber University	Participation as researcher from academia	
	20	Kyoung Hee University	Participation as researcher from academia	Focus-group
	21	Kyoung Hee University	Participation as researcher from academia	Focus-group
	22	Seoul National University of Science and Technology	Participation as researcher from academia	

Case 5: Measurement Science Roadmap for Metal-Based Additive Manufacturing (NIST 2013)	23	NIST	Administration of overall roadmapping processes	Focus-group
	24	NIST	Administration of overall roadmapping processes	Focus-group
Case 6: NIST Framework and Roadmap for Smart Grid Interoperability Standards (NIST 2010)	25	NIST	Administration of overall roadmapping processes	3 interviews
	26	NIST	Administration of overall roadmapping processes	Via phone
	27	NIST	Administration of overall roadmapping processes	Focus-group
	28	NIST	Administration of overall roadmapping processes	Focus-group
	29	NIST	Administration of overall roadmapping processes	Focus-group
	30	NIST	Administration of overall roadmapping processes	
Case 7: The German Standardisation Roadmap for Electromobility (NPE 2012)	31	DIN	Administration of overall roadmapping processes	Via phone
	32	Fraunhofer Institute for Structural Durability and System Reliability LBF	Participation as researcher from laboratory	Via e-mail

* Note: See page xvi for definitions of the abbreviations.

Table A.3 Profiles of interviewees in the in-depth case study of PV technology

Expert #	Organisation	Experience / Perspective in PV Standardisation	Participating SDOs	Note
1	Whitfield Solar	Participation from industry	IEC	Via phone
2	Jacobs University	Participation as researcher from academia / Strategic management in international SDO	SEMI	Via phone
3	University of Strathclyde	Participation as researcher from academia / Participation from industry	IEC	Via phone
4	Sunset Technology	Participation from industry	IEC	Via e-mail
5	IEC	Strategic management in international SDO	IEC	Via e-mail
6	BSI	Participation from standards organisations	SEMI	Via e-mail
7	BEW Engineering	Participation from industry	IEC, IEEE	2 interviews
8	Enphase Energy	Participation from industry	IEEE	
9	PowerMark	Participation as an independent consultant / Participation from industry	IEC, IEEE	
10	Atlas Material Testing Technology	Participation from industry	IEC	
11	NREL	Participation as researcher from laboratory	IEC	
12	3M	Participation from industry	IEC	
13	NREL	Participation as researcher from laboratory	ASTM	
14	NREL	Participation as researcher from laboratory	IEC	
15	CPVSTAR Consulting	Participation as an independent consultant	IEC	
16	NREL	Participation as researcher from laboratory	IEC	
17	Larry Sherwood & Associates	Administration of Solar ABC		
18	NREL	Participation as researcher from laboratory	IEEE	
19	NREL	Participation as researcher from laboratory	ASTM	
20	NREL	Participation as researcher from laboratory	IEC	2 interviews
21	NREL	Participation as researcher from laboratory	ASTM	
22	NREL	Participation as researcher from laboratory	IEC	2 interviews
23	Spire Solar	Participation from industry	IEC	
24	Spire Solar	Participation from industry	IEC	
25	National Grid	Participation from industry	IEEE	Via phone
26	SEIA	Participation as an independent consultant / Participation from industry	IEEE	
27	IEC	Participation as an independent consultant / Participation from industry / Strategic management in international SDO	ASTM, IEC	3 interviews
28	SunEdison	Participation from industry	IEC	
29	DOE	Participation from government agency	IEC	2 interviews
30	NABCEP	Participation from industry		Via phone
31	NIST	Participation as researcher from laboratory	IEC	

32	University of Delaware	Participation as researcher from academia	IEC	Via e-mail
33	NRECA	Participation from industry	IEEE	
34	NREL	Participation as researcher from laboratory	ASTM	
35	NIST	Participation as researcher from laboratory	ASTM	
36	DOE	Support for standardisation activities from government agency		
37	DOE	Support for standardisation activities from government agency		
38	University of NSW	Academic research on PV standardisation		
39	UL	Participation as researcher from laboratory	IEC	
40	ARCO Solar (past)	Participation as an independent consultant	ASTM	
41	NASA (past)	Participation as researcher from laboratory		
42	TetraSun	Participation from industry	IEC	

* Note: See page xvi for definitions of the abbreviations.

Appendix B – Interview Protocols for the In-depth Case Study of PV Technology (Based on the *Expert Scan* Method)

Opening questions

1) Please briefly describe your experiences with PV standardisation.
2) Are any of these events (shown on the map) particularly related to key standardisation activities of PV technology?
   a) What triggered, or led those standardisation activities?
   b) What impacts did those standardisation activities have on other activities?
3) Are there any other key events not shown on the map? How are they related to key standardisation activities of PV technology?
4) What do you think were the most important / influential standardisation activities relevant in the innovation of PV technology?
5) Were there any cases where premature / ill-anticipated / poorly-designed standards were developed, resulting in negative impacts on the innovation of PV technology?
   a) Any cases where standards had to be completely disregarded, or radically revised later?
   b) Any cases where better alignment / harmonisation was required?

Questions regarding specific standardisation activities that interviewees worked on

1) What were the context / motivation of developing the particular standard?
2) What kind of knowledge did it codify?
3) How did it support knowledge transfer between different innovation activities / stakeholders?
4) How did such knowledge transfer support the innovation of PV technology?
5) What categories best describe the standard in terms of the following dimensions? (Please suggest other dimensions if necessary.)
   a) Type of technology elements (‘*what*’)
   b) Roles / functions (‘*why*’)
   c) Timing of standards (‘*when*’)
   d) Form of standards (‘*how*’)

    e) Stakeholders involved (‘*who*’)

6) Which of these dimensions / categories were considered to be more important? Why?
7) Are there any relationships / interdependences between these dimensions? Which of them were the most significant?
8) How did they evolve over time throughout the PV innovation journey?

Appendix C – Existing Standardisation Roadmaps

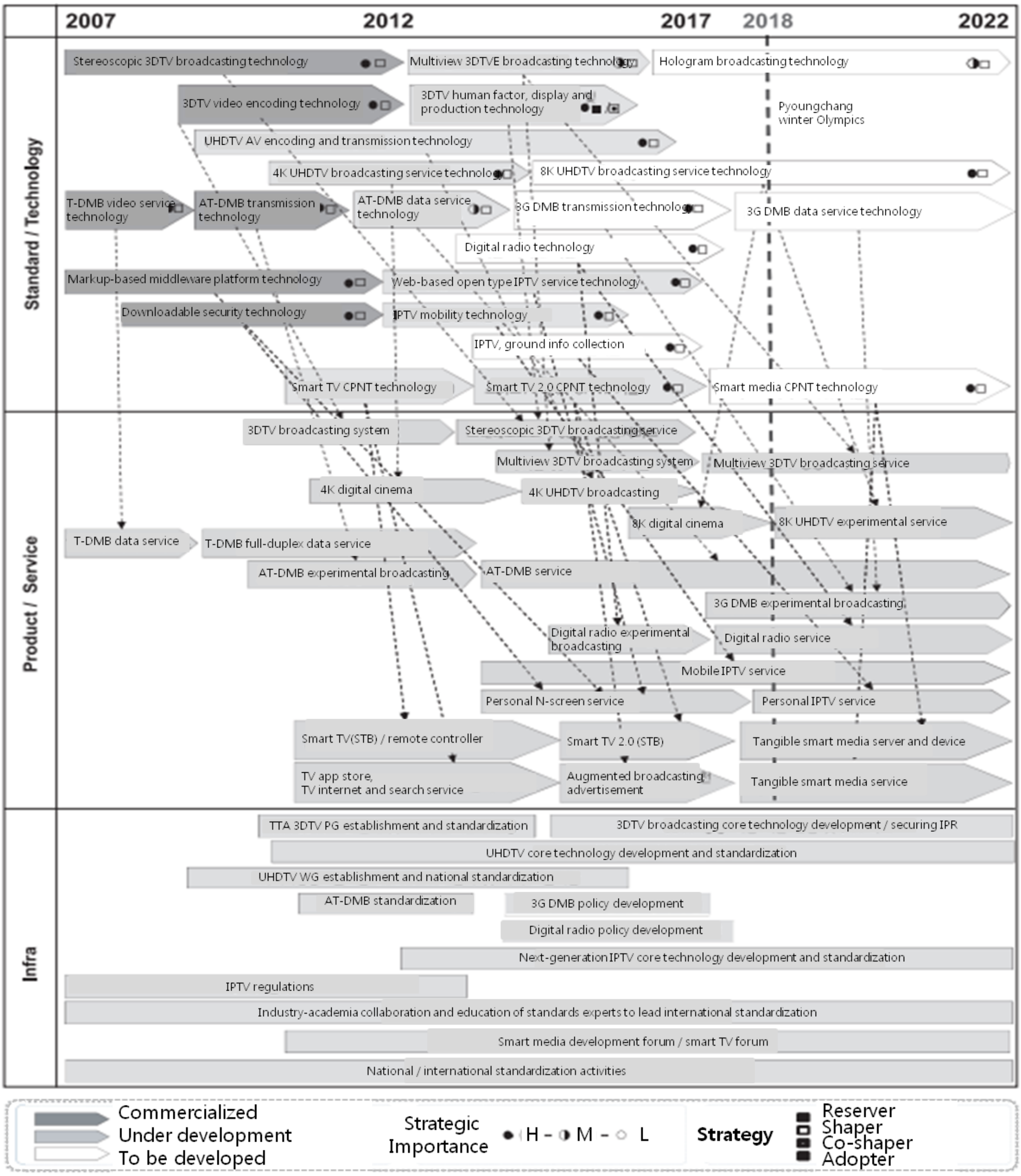
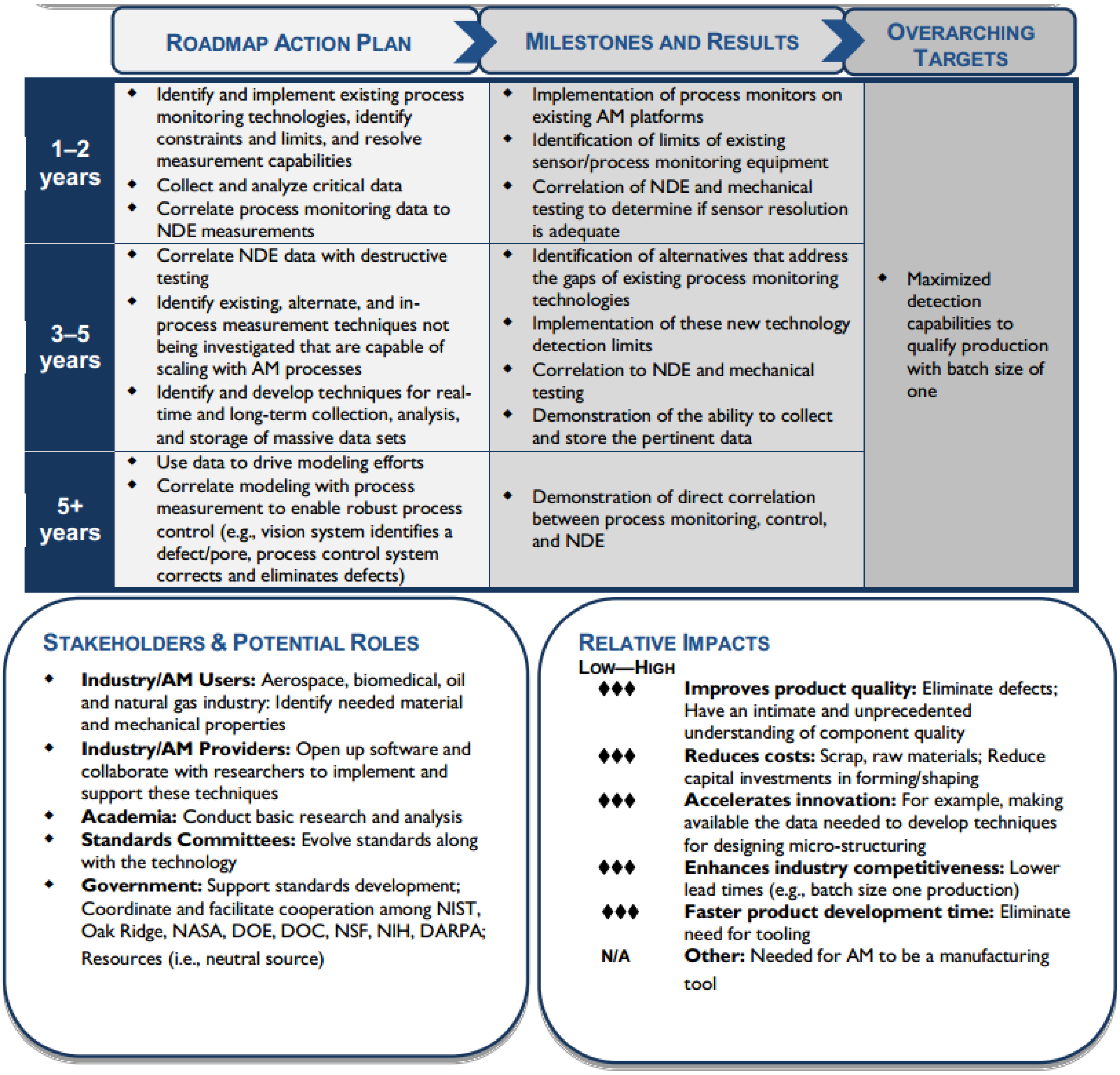


Figure A.1 Example of ICT standardisation strategy map – case of 3DTV (translated from Korean by the author, TTA 2013, p.10)



	Roadmap Action Plan	Milestones and Results	Overarching Targets
1–2 years	• Identify and implement existing process monitoring technologies, identify constraints and limits, and resolve measurement capabilities • Collect and analyze critical data • Correlate process monitoring data to NDE measurements	• Implementation of process monitors on existing AM platforms • Identification of limits of existing sensor/process monitoring equipment • Correlation of NDE and mechanical testing to determine if sensor resolution is adequate	• Maximized detection capabilities to qualify production with batch size of one
3–5 years	• Correlate NDE data with destructive testing • Identify existing, alternate, and in-process measurement techniques not being investigated that are capable of scaling with AM processes • Identify and develop techniques for real-time and long-term collection, analysis, and storage of massive data sets	• Identification of alternatives that address the gaps of existing process monitoring technologies • Implementation of these new technology detection limits • Correlation to NDE and mechanical testing • Demonstration of the ability to collect and store the pertinent data	
5+ years	• Use data to drive modeling efforts • Correlate modeling with process measurement to enable robust process control (e.g., vision system identifies a defect/pore, process control system corrects and eliminates defects)	• Demonstration of direct correlation between process monitoring, control, and NDE	

Stakeholders & Potential Roles

- **Industry/AM Users:** Aerospace, biomedical, oil and natural gas industry: Identify needed material and mechanical properties
- **Industry/AM Providers:** Open up software and collaborate with researchers to implement and support these techniques
- **Academia:** Conduct basic research and analysis
- **Standards Committees:** Evolve standards along with the technology
- **Government:** Support standards development; Coordinate and facilitate cooperation among NIST, Oak Ridge, NASA, DOE, DOC, NSF, NIH, DARPA; Resources (i.e., neutral source)

Relative Impacts

Low—High

♦♦♦	**Improves product quality:** Eliminate defects; Have an intimate and unprecedented understanding of component quality
♦♦♦	**Reduces costs:** Scrap, raw materials; Reduce capital investments in forming/shaping
♦♦♦	**Accelerates innovation:** For example, making available the data needed to develop techniques for designing micro-structuring
♦♦♦	**Enhances industry competitiveness:** Lower lead times (e.g., batch size one production)
♦♦♦	**Faster product development time:** Eliminate need for tooling
N/A	**Other:** Needed for AM to be a manufacturing tool

Figure A.2 Example of roadmap action plan in measurement science roadmap for metal-based additive manufacturing (NIST 2013, p.10)

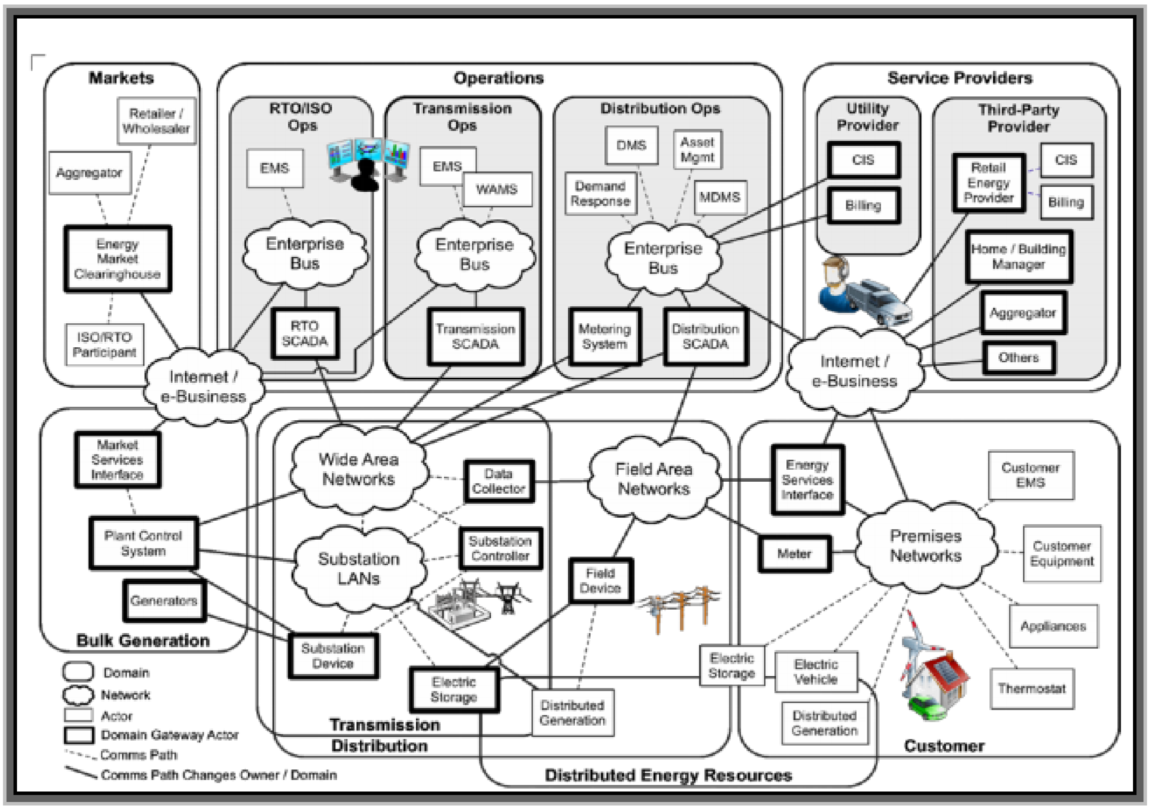


Figure A.3 Example of system architectures used in NIST smart grid roadmap (NIST 2010, p.35)

Appendix D – Details of Features Included in Framework and Process Model

Table A.4 Dimensions and sub-categories included in standardisation mapping framework

Dimension	Sub-Category	Brief Explanation	Evidence*
WHAT	**Industry Environment**	General activities of the industry outside the innovation system	Case 10
	Policy / Regulation	Political and legal issues, such as industrial policy, trade and competition, and regulations	Case 3, Case 10
	Market / Customers	Commercialisation and market development	Literature, Case 2, Case 3, Case 10
	Business / Service	Firms' activities to provide business solutions / services	Literature, Case 3, Case 10
	Supply Network	Transactions within supply networks, involving materials, components, equipment, etc.	Case 2, Case 10
	System	Overall system of technologies integrating various components	Literature, Case 1, Case 2, Case 3, Case 10
	Production	Particular procedure or process executed for efficient production of products / applications	Literature, Case 2, Case 3, Case 10
	Product / Application	Actual market applications formulated from generic technology to perform specific tasks / functions	Literature, Case 1, Case 2, Case 3, Case 10
	Proprietary Technology	Applied research where generic technology is configured / reconfigured into specific prototypes	Literature, Case 2, Case 10
	Generic technology	Fundamental technical concepts derived from basic science for specific product innovations	Literature, Case 1, Case 2, Case 10
	Infratechnologies	Varied and critical technical infrastructure that derive from a different technical base from that of product's attributes, including applied / industrial metrology	Literature, Case 1, Case 2, Case 10
	Science Base	Basic scientific principles representing fundamental laws, including basic metrology	Literature, Case 1, Case 2, Case 10
WHY	**Terminology / Semantic Standards**	Define common language and definitions to facilitate efficient communication among stakeholders	Literature, Case 1, Case 2, Case 3, Case 10
	Measurement / Characterisation Standards	Specify methods for describing, quantifying, and evaluating product attributes for efficient R&D	Literature, Case 1, Case 2, Case 3, Case 10
	Quality / Reliability Standards	Specify acceptable performance criteria along certain dimensions	Literature, Case 2, Case 3, Case 10
	Compatibility / Interface Standards	Specify properties that a technology must have in order to be compatible (physically or functionally)	Literature, Case 1, Case 2, Case 3, Case 10
	Variety-reduction Standards	Limit a certain range or number of characteristics such as size	Literature, Case 3, Case 10

WHEN	**Real-time**		Case 1, Case 3, Case 10
	Relative to Technology Lifecycles		
	Anticipatory Standards	Specified at the introduction of technology	Literature, Case 10
	Participatory Standards	Developed in parallel with market growth and enhancements to technology and product	Literature, Case 10
	Responsive Standards	Developed at the end of technology development	Literature, Case 10
HOW	**Types of Deliverables**		
	e.g. IS / EN	Developed for topics with the highest level of maturity and a high degree of consensus among various actors	Case 2, Case 3, Case 10
	e.g. TS / PAS / WA	Developed for topics which have not reached a sufficient state of maturity or degree of consensus	Case 1, Case 10
	Form of Specifications		
	Performance Standards	Specify desired outcomes or performance levels	Case 2, Case 3, Case 10
	Solution-Describing / Prescriptive Standards	Provide detailed descriptions or precise specifications for exactly how solutions could achieve outcomes	Case 1, Case 2, Case 3, Case 10
WHO	**Organisations Leading Standardisation**		
	De facto standards	Usually driven by market forces, either voluntarily formed or established through standard battles. Often begin as industry or proprietary standards developed by private companies or trade associations for internal use.	Case 10
	De jure standards	Developed and approved by recognised standard bodies through the formal consensus-based process	
	- FSOs	National SDOs (e.g. BSI, DIN), regional SDOs (e.g. CEN, CENELEC), or international SDOs (e.g. ISO, IEC, and ITU), formally recognised by an authority and operating through governmental representations	Case 2, Case 3, Case 10
	- SSOs	Professional or specialist organisations in particular business sectors or professional disciplines. e.g. ASTM, IEEE	Case 2, Case 3, Case 10
	- Consortia / Research Initiatives	Formed by like-minded interests, often focusing on well-defined projects. e.g. W3C, IETF, BioBricks	Case 1, Case 3, Case 10
	Stakeholders Involved in Standardisation (can be also categorised according to roles / motivations)		
	Consumers	End-users of products / systems affected by standards.	Case 2, Case 3, Case 10
	Government	Public sector bodies as supporters / users of standardisation.	Case 3, Case 10
	Industry (companies)	Producers / users of products affected by standards.	Case 1, Case 2, Case 3, Case 10
	Consultants	Professionals with technology know-how, e.g. consultancy firms, independent consultants.	Case 1, Case 2, Case 3, Case 10
	Researchers	Scientists / engineers from research laboratories (public / private) or academia.	Case 1, Case 2, Case 3, Case 10
	Others	e.g. labour (trade associations), NGOs, training entities.	Case 10, Interview

Table A.5 Steps included in process model for using framework for standardisation foresight

Phase	Steps of the process model	Evidence*
Initiation & planning	0a: Gather existing information / preliminary insights	Case 4, Case 5, Case 6, Case 7
	0b: Identify scope	Literature, Case 4, Case 5, Case 6, Interviews
	0c: Decide processes & participants	Literature, Case 4, Case 5, Case 6, Case 7, Interviews
	1a: Identify vision & goals	Literature, Case 4, Case 5, Case 6, Case 7, Case 8, Case 9, Interviews
	1b: Define fundamental concepts	Case 4, Case 5, Case 6, Case 7, Case 8, Case 9
Input & analysis	2a: Design basic system architecture	Case 6, Case 8, Case 10, Interviews
	2b: Identify current standards	Literature, Case 4, Case 5, Case 6, Case 7, Case 8, Case 9, Interviews
	3a: Analysis of (inter)national environment: technical issues	Case 4, Case 5, Case 6, Case 7, Case 9, Case 10, Interviews
	3b: Analysis of (inter)national environment: non-technical issues	Literature, Case 4, Case 5, Case 6, Case 7, Case 9, Interviews
	4a: Gap analysis	Case 4, Case 5, Case 6, Case 7, Case 8
	4b: Refine system architecture	Case 6, Case 10
Synthesis & output	4c: Establish priorities	Case 4, Case 5, Case 7
	4c: Develop and review action plans	Literature, Case 4, Case 5, Case 6, Case 7, Case 9, Interviews
	5: Publication & implementation	Literature, Case 4, Case 5, Case 6, Case 7, Case 8, Case 9
Follow-up	6a: Evaluation of foresight process	Literature, Case 4, Case 5, Case 6
	6b: Review of implementation	Case 10
	6c: Review and assessment of outputs	Case 6, Interviews

* Note: ‘Literature’, ‘Case 10’, and ‘Interviews’ indicate the initial review of academic literature (section 5.1), the in-depth case of PV (Chapter 6), and verification interviews (Chapter 7), respectively. This applies to both Tables A.4 and A.5.