The Multi-Dimensional Nature of Standardisation in Support of Innovation: A Systematic Analysis of the History of Photovoltaic Technology

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***Abstract**: Despite increasing awareness of the critical role of standards in technological innovation, there remain significant challenges to managing standardisation activities in a timely and effective manner. This is due to limited understandings of complex dynamics between standardisation and innovation; different types of standards, developed by different sets of innovation actors, support a variety of innovation activities, at different stages of technological and industrial lifecycles. In order to overcome these challenges, recent theory-building efforts have led to the development of a novel systematic framework which carefully articulates and characterises important dimensions of standardisation in the context of technological innovation. Testing and building on this framework, this paper presents a systematic analysis of the history of photovoltaic (PV) technology and relevant standardisation. This case study not only demonstrates the importance of the multi-dimensional nature of standardisation in understanding how they support innovation, but also identifies a number of interesting patterns and trends, increasing our understandings of complex dynamics between standardisation and innovation. In addition, the case study provides additional insights for minor improvements of the framework itself. Capturing important aspects and issues to be considered for strategic management of standardisation, the refined framework is expected to support standards organisations and policymakers for more systematic and future-oriented analyses of standardisation in support of overall technological innovation.*

1. Introduction

With the prevalence of innovation system perspectives, standards have been increasingly recognised as important institutions that underpin technological innovation by disseminating new ideas and transferring useful knowledge (CIE, 2006; Hawkins, 1995). Several recent studies have thus explored various roles of standards in supporting innovation, including: defining and establishing common foundations upon which innovative technology may be developed; codifying and diffusing state of the art technology; and allowing interoperability between and across products and systems (Allen & Sriram, 2000; Blind & Gauch, 2009; Swann, 2010; Tassey, 2000). Recognising such critical roles, many countries increasingly adopt policy initiatives for effective standardisation of key technologies, in order to secure national competitiveness and support their innovation systems (Biddle et al., 2012; Lord Heseltine, 2012; White House, 2011).

Due to the dual nature of standards, however, strategic management for careful planning and implementation of standards is critical in supporting technological innovation more effectively. A standard that is imposed too early hinders diversity and precludes entrepreneurial experiences, closing opportunities for further technological improvement and promising innovation; whereas a standard that comes too late may not only retard achieving economies of scale for new market development, but also result in unnecessary costs of duplication and market confusion, both of which are potentially detrimental to innovation (CIE, 2006; Foray, 1998). Inappropriate standards may also have negative impacts on innovation, such as risks of monopoly and problems of lock-ins into inferior standards (CIE, 2006). Hence, there are needs for more future-oriented analyses to anticipate standards needs and develop standardisation strategies, in order to better support innovation of emerging technologies (European Commission, 2011; Scapolo et al., 2013).

Despite such increasing importance of strategic foresight and management of standardisation at a public policy level, there are limited understandings and academic literature on anticipation and strategy development for standardisation in broader innovation systems. Such limited knowledge is probably due to not only the complex and uncertain nature of technological innovation systems, but also variations and confusions that are prevalent with standardisation. There are actually various definitions of standards used in different ways in different contexts, depending on purposes and interests identified by different parties (de Vries, 1999). In fact, there are various types of standards playing different roles, associated with varying levels of technical details, and developed by a variety of stakeholders with different interests (Allen & Sriram, 2000; Blind, Gauch, & Hawkins, 2010; Sherif, 2001; Swann, 2010; Tassey, 2000). These complexities are further complicated by the fact that they not only interact with each other, but also evolve over time as innovation progresses. Such varieties and complexities involved in standardisation can be also observed from inconsistent classifications on important dimensions and aspects of standardisation in existing literature (e.g. Verman 1973; Branscomb & Kahin 1995; Baskin et al. 1998). Hence, it is extremely challenging to characterise and understand complex dynamics between standardisation and innovation, which are critical information for strategic management of standardisation.

The challenge with effective management of standardisation in support of innovation is becoming even more significant with the recent trend in modern technology-based industries that are interdisciplinary, integrated, and rapidly evolving at the same time. The increasing complexity of modern industries due to their systems characteristic requires a large infrastructure of standards that allow integration of various domains with different technology bases (NPE, 2012; Tassey, 2015). The growing importance of Information and Communications Technology (ICT) in many areas – including smart grid and internet of things, just to name a few – also presents significant challenges of anticipating future standards needs to ensure compatibility and interoperability, especially during earlier stages of innovation with high uncertainties and risks (Biddle et al., 2012; Ernst, 2009). In addition, there are demands for more timely and efficient standardisation activities that respond rapidly to evolving technical needs, in order to gain competitive advantage in the fast changing global landscape and economic environment (European Commission, 2011).

In order to address these challenges, there have been a number of academic efforts to develop a systematic framework for more effective and future-oriented analyses of complex dynamics between standardisation and innovation (Egyedi, 1996; Featherston, Ho, Brévignon-Dodin, & O'Sullivan, 2016; Ho & O'Sullivan, 2015a). Verifying and building on these frameworks, the current research presents a historical case study of photovoltaic (PV) technology. By taking a multi-dimensional approach to analyse how standards support PV innovation, this case study illustrates various dimensions of standardisation, demonstrating their importance for strategic standardisation. In addition, the case study not only increases our understandings of standardisation dynamics in the context of innovation, but also provides additional insights for further refinements of existing frameworks. With more careful articulation and characterisation of critical aspects associated with standardisation, the improved framework is expected to help standards organisations and policymakers make more informed decisions, ensuring effective management of standardisation in support of their innovation systems.

2. Existing Frameworks for Systematic Analyses of Standardisation

Despite increasing awareness of their important roles in supporting innovation, previous academic research on standards and standardisation in the context of technological innovation are limited, generally focusing on a particular technical discipline or a specific standard item (Cargill, 1995; de Vries, 2001). They also have narrow views on standards, addressing certain aspects of standardisation only, usually economic perspectives (Branscomb & Kahin, 1995; de Vries, 2001; Hawkins, 1995). From a systematic review of papers on technology standards, Narayanan & Chen (2012) observe that scholars adopt divergent perspectives with different levels of analysis and different ontological assumptions, yet are confined within a single perspective rather than taking multiple perspectives. Lyytinen et al. (2008) also identify four broad theoretical perspectives adopted in existing literature on ICT standardisation: economic and management theories, legal and public policy studies, social theories, and standardisation practice. Hence, there are fragmented bodies of literature exploring standardisation in various disciplines adopting different perspectives (Choi, Lee, & Sung, 2011; de Vries, 1999).

Consequently, existing frameworks presented in previous academic research provide only partial pictures of standardisation in the context of innovation, focusing on different aspects. For example, Tassey (2000) proposes a framework representing various types of standards used in different industrial activities – including R&D, production, and market penetration – for efficient development and utilisation of technology. Sherif (2001), on the other hand, proposes a framework relating different categories and roles of standards with technology lifecycles – often referred to as S-curve – in the context of ICT. A more recent framework is developed by Blind & Gauch (2009), showing various roles and functions of standards at different stages of innovation processes. Emphasising different aspects of standardisation in the context of innovation, such lack of holistic and integrated perspective results in fragmented and limited understandings of overall dynamics between them.

In fact, there is a high degree of complexity and diversity in various aspects of standardisation, all interacting with each other. There are various forms of standards, each playing different roles and functions, associated with varying levels of technical details, and developed by a diverse mix of stakeholders, all of which evolve over time along with technology lifecycles (Allen & Sriram, 2000; Blind & Gauch, 2009; CIE, 2006; Sherif, 2001; Swann, 2010; Tassey, 2015). For example, in a rapidly evolving field of nanotechnology, there are various standards developed by a variety of organisations, each addressing different issues and interacting with different aspects of innovation (Murashov & Howard, 2011). From our preliminary studies to explore standardisation of PV technology, empirical evidence also suggests that different types of standards with different roles and functions, developed by different Standards Developing Organisations (SDOs) engaging different set of stakeholders, emerge across different stages of innovation (Ho & O'Sullivan, 2013, 2015b). Due to such varieties and complex dynamics involved in standardisation, slight variations may produce very different results, so increasing uncertainties in anticipating, or even analysing, what impacts they have on innovation.

A holistic and integrative approach accounting for various aspects of standardisation utilising multiple perspectives is thus called for, in order to analyse the complex problem of standardisation in the context of innovation in a more comprehensive way (Bonino & Spring, 1999; Narayanan & Chen, 2012). By addressing complexities and varieties involved in both standardisation and technological innovation, a number of scholars have recently taken broader and more integrated approaches. Identifying standardisation as a context of technology development, Egyedi (1996) presents a coherent and comprehensive view on standardisation by adopting the three social constructivist perspectives: institutional, political, and socio-cognitive perspectives. Recognising needs to treat standardisation in its entirety, Garcia et al. (2005) employ the notion of organisational fields to adequately assess impacts and characterise its relationships with other innovation activities. {Formatting Citation}, on the other hand, adopt a technology roadmapping approach in developing a framework for supporting the anticipation of standards to inform emerging technology strategies.

Providing a coherent, holistic, and high-level integrated view of complex systems, while displaying the interactions between technologies and other aspects of innovation over time, technology roadmap-based frameworks appear particularly useful in analysing complex dynamics between standardisation and innovation (Groenveld, 2007; Kostoff & Schaller, 2001; Phaal, Farrukh, & Probert, 2010; Popper, 2008). Featherston et al. (2016) suggest that as one of the most widely used foresight tools, the roadmap-based framework can be also used to inform the development of standardisation strategies, as its process – which brings together various stakeholders to build consensus and create a common vision among them (Amer & Daim, 2010; Groenveld, 2007; Popper, 2008) – is similar to the process of standardisation. By carefully identifying key activities in the innovation process and linking them with associated standardisation opportunities, their framework helps identify where standards may support knowledge diffusion and mediate innovation actors. In particular, the framework identifies a number of important factors of standardisation – including technological activities, types of standards, timing of standardisation, and SDOs and participants involved in standardisation – with special attentions paid to different categories of technologies involved in innovation. However, it is not a coherent and complete list of all critical factors and characteristics of standardisation related to technological innovation; for instance, factors such as types of deliverables or forms of specifications, are not included.

Ho & O'Sullivan (2015a) present a more systematic and refined roadmap-based framework that is grounded on theoretical analyses, through a comprehensive review of literature on various aspects of standardisation. Using an analytical framework consisting of six questions that are often used to describe any forms of human activity – i.e., what, why, when, how, who, and where, as adopted by Baskin et al. (1998) and Sherif (2001) –, a coherent and integrated list of important dimensions of standardisation in the context of technological innovation is identified. They include *what* technology elements to standardise, *why* standards are needed, *when* to standardise, *how* to standardise, and *who* is leading or involved in standardisation. Although the issue of *where* standardisation is carried out have significant implications for standardisation landscapes, such as types of SDOs and their responsibilities, these vary significantly depending on national and regional contexts, including culture and history of institutional systems; it is thus suggested to be the best not to further categorise the issue of *where* and keep distinctions simply regarding the issue of *who*. These key dimensions and issues of standardisation are then incorporated in the framework proposed by Featherston et al. (2016), as shown in Figure 1. By carefully articulating and categorising all important dimensions of standardisation and capturing them in a holistic way, it is a more comprehensive and systematic framework than any previous models (e.g. Tassey 2000; Sherif 2001; Blind & Gauch 2009). Thus effectively representing the multi-dimensional nature of standardisation and how these dimensions interplay with each other, the framework can be a useful tool for not only analysing complex dynamics between standardisation and innovation, but also assisting strategic management of standardisation in support of innovation.

In order to demonstrate how this framework can support systematic and future-oriented analyses of standardisation and test the validity of its dimensions and their sub-categories, this paper presents a multi-dimensional analysis of standardisation in the context of PV. From the historical analysis of PV technology and relevant standardisation activities, the case study illustrates how various dimensions of standardisation incorporated in the framework are critical for understanding these complex dynamics between standardisation and innovation. It is also suggested from the case study that the proposed framework, by carefully capturing all these important dimensions, can effectively support strategic management of standardisation.

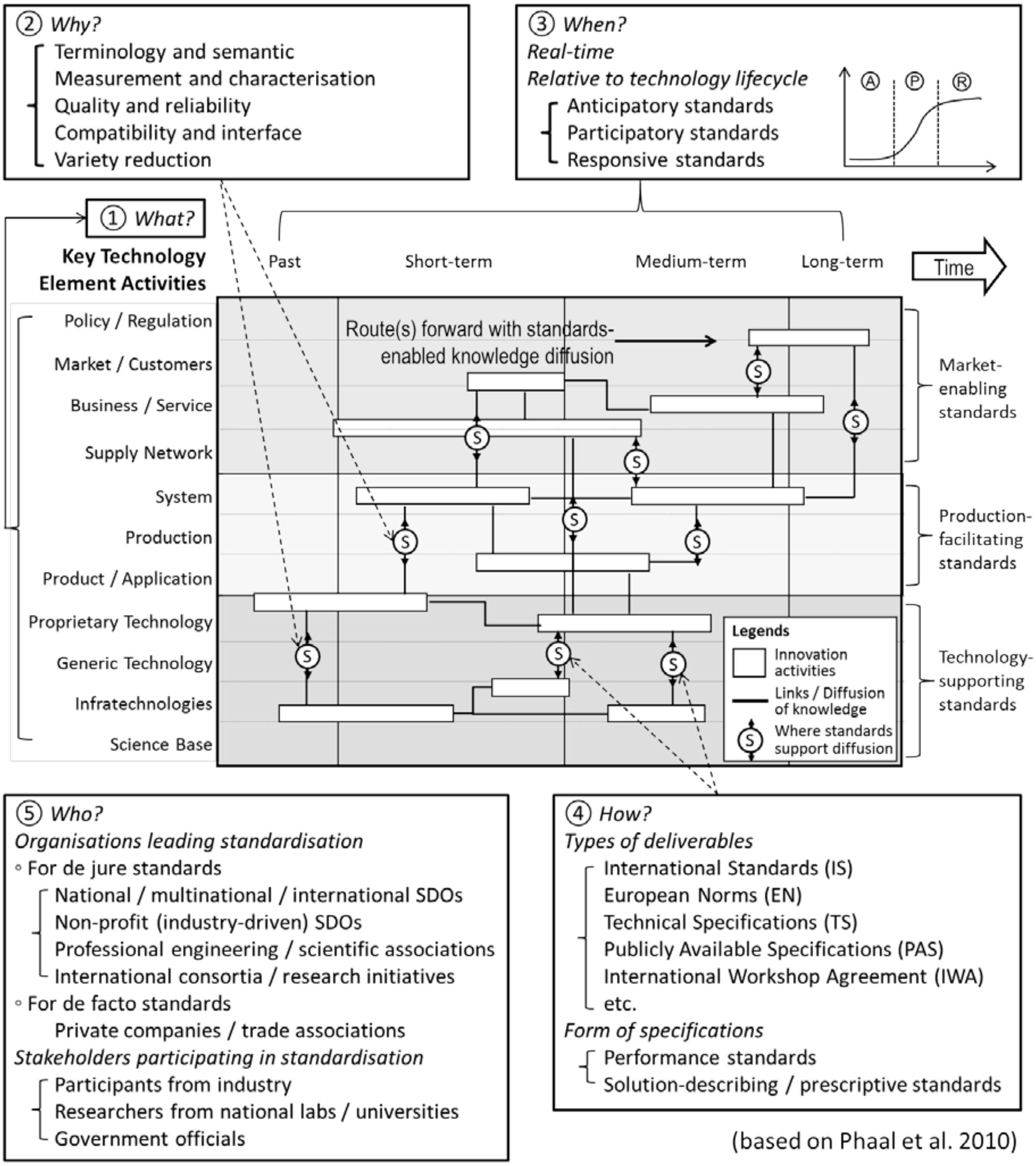

Figure 1*. Framework for anticipating standardisation needs* (Ho & O'Sullivan, 2015a)

3. Case Study of PV Technology

The case of PV technology is selected for this study, because of its various application areas, a variety of stakeholders involved, and a high level of systems complexity, all of which add intricacy and variety to its standardisation activities. Along with its long history of development, they provide rich information to explore various issues associated with complex dynamics between standardisation and innovation. In particular, the case study starts exploring standardisation in the innovation context of the US, as they dominated early PV standardisation. As the birthplace of PV technology, most of early innovation and development activities of PV took place in the US; PV standards developed by standards organisations based in the US thus had significant influences in international standardisation activities later. As international perspectives became increasingly important in standardisation with the development of international PV markets, the study later expands its scope to cover international context as well. Nevertheless, it is to be noted that early PV standardisation is greatly influenced by its national context and particular standardisation landscape of the US.

Given retrospective nature of the research, over 200 archival documents from various sources and perspectives – including standard publications, industry trade magazines, official reports published by governments and research laboratories, and journal articles – have been collected. Although many of these documents are available in the public domain, key documents and insights were 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 archival data, as well as the rich description offered in the PV industrial roadmap developed by Friligos (2010), were used to identify key events and activities during the historical development and standardisation of PV technology.

Semi-structured interviews were also carried out with experts who have been involved in various PV standardisation activities. Interviews not only complement documental resources by providing contextual backgrounds and details which might be difficult to access through document sources alone, but also generate insights into any relationships and linkages between key events. Archival documents, as well as preliminary studies exploring both quantitatively and qualitatively standardisation of PV technology (Ho & O'Sullivan, 2013, 2015b), have been drawn upon to inform and design interview questions. Interviewees are initially contacted from the list of members in technical committees for PV in major SDOs (ASTM E44, IEC TC82, IEEE SCC21, and PV Committee in SEMI), then approached using "snowball sampling" (Goodman, 1961). A total of 42 experts from a variety of organisations – including private companies, national laboratories, governments, and academia – across various areas of PV technology participated in interviews, ensuring the balanced representation of varied perspectives. It is to be noted that although most of them are from the US, key interviewees also have strong understandings of international perspectives of PV standardisation, based on their experiences in international committees.

Based on these data, detailed descriptions for complex dynamics of standardisation throughout the innovation journey of PV technology are presented in a narrative style. Structured in chronological order, the narrative is also captured and visualised using the roadmap-based framework, as shown in Figure 2; only major events and milestones are included here for practical reasons, especially ones relevant to standardisation activities explored in this case study (i.e. gaps in the roadmap doesn't mean that there are no activities, but activities are less significant or relevant to key standardisation). The figure includes the main framework depicting the overall narrative in the centre, as well as smaller frameworks focusing on certain periods of time for detailed illustrations of complex dynamics between innovation and standardisation in different phases of PV history. There are four broad phases of the PV innovation journey, divided according to the evolution of their main application areas: (i) transition from space applications to terrestrial applications (1976~1985), (ii) demonstration of grid-connected applications (1986~1995), (iii) introduction of large power systems (1996~2005), and (iv) emergence of smart grid (2006~2016). Key standardisation activities in each phase and their relationships with other innovation activities are explored and captured in the roadmap-based framework. Each standard and their key dimensions – *what, why, when, how,* and *who,* as identified in Figure 1 – highlighted in the case study are discussed in the following.

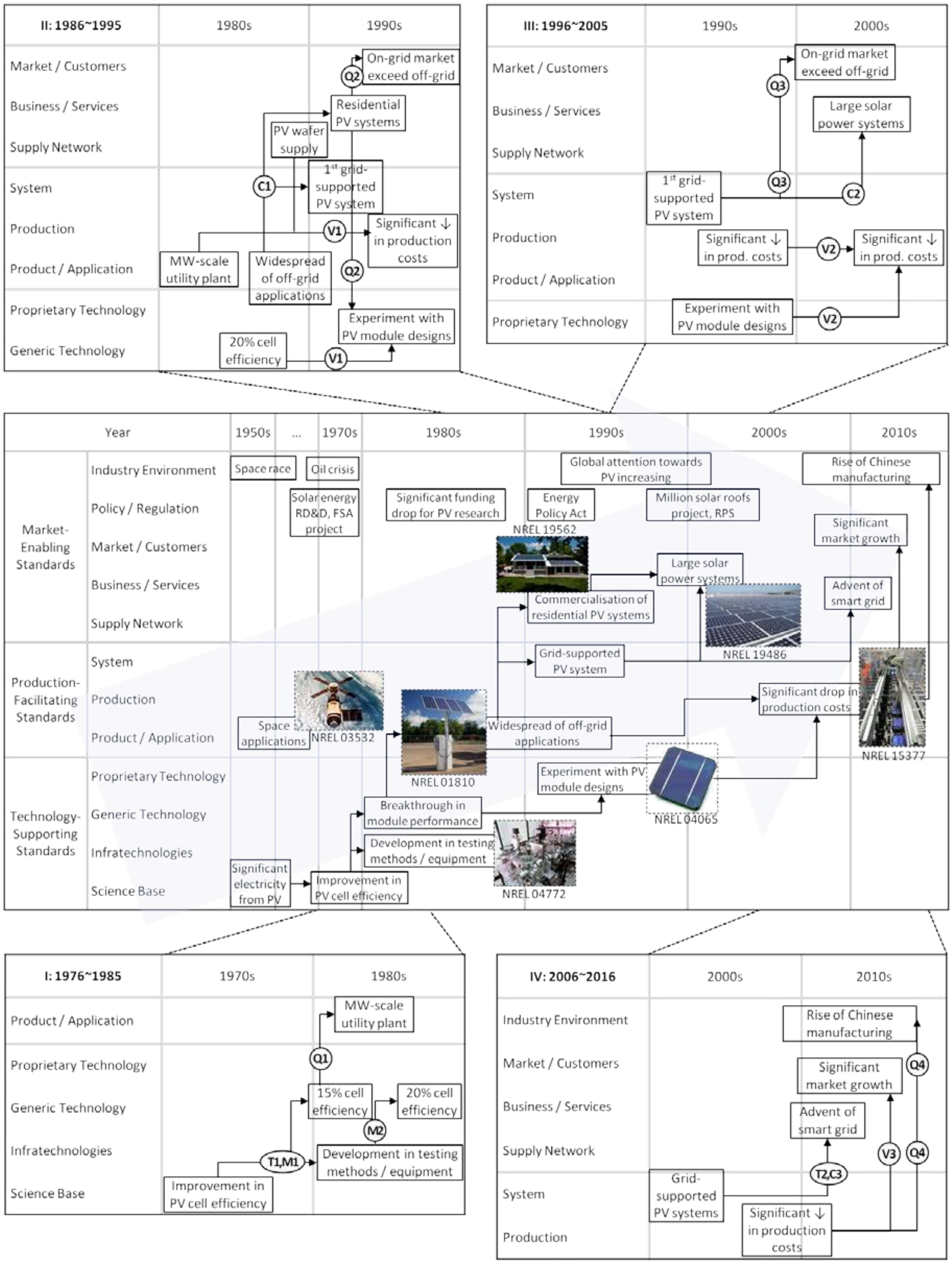

Figure 2. Systematic analyses of PV standardisation (all images from NREL 2016)

3.1 Transition from a niche market of space applications to terrestrial applications for wider public (1976~1985)

Although electricity generated from the PV effect was first observed at Bell Laboratory in 1954, the technology remained in the niche market of space applications until the oil crisis in the 1970s, when PV gained great attentions as an alternative source of energy (Ksenya, 2011). In order to address the problem of energy security, various government programs were proposed – including Energy Research and Development Administration (ERDA)'s National PV Program – supporting terrestrial applications of PV, and needs for appropriate standards were identified among the growing number of stakeholders involved in PV (Ross & Smokler, 1986). Consequently, two PV Measurement Workshops were organised by ERDA, resulting in the technical report (NASA TM 73702) which presented the first set of consensus-based standards (NASA, 1977). Although nearly 60 people from all sectors of the PV community participated in workshops, an interviewee noted that a large number of them was researchers from government laboratories – such as the National Aeronautics and Space Administration (NASA)'s Lewis Research Centre, Jet Propulsion Laboratory (JPL), and Sandia Laboratory – as they were more experienced in this emerging area with niche market of space applications.

T1: Terminology standard for PV technology

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

M1: Measurement / testing standards for PV cells and modules

The report also consisted of reference spectrum, standard test conditions, equipment, and procedures to be used in testing and measurement of cell performances (NASA, 1977). According to interviewees, having a standard method of measurement made it easier to not only compare performances of cells developed by different researchers, but also accurately assess the current status of technology development through rigorous traceability. An interviewee added that accurate assessment of research deliverables were particularly valuable for program managers and funding agencies to make decisions about funding, guiding research directions for technology improvement. Therefore, terminology and measurement standards included in the NASA report increased accuracy and efficiency of PV research, facilitating the development of both PV cells and technical infrastructure required to support technological development (including measurement methods and standard databases).

Q1: Qualification testing specifications for PV modules

Despite the significant improvement of generic technology in late 1970s, widely used terrestrial applications did not exist due to the lack of reliable and economically viable PV modules; many interviewees noted that customers (such as government and installation companies) were reluctant to use PV modules and panels, as early modules developed in 70s-80s frequently failed in the field due to low quality and reliability. Hence, the US government initiated the Flat-Plate Solar Array (FSA) Project at JPL, for an effective cooperative efforts between researchers and industry 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, Vidican, & Lester, 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 not only helped designers and manufacturers to develop products with higher quality, but also ensured customers to have confidence in module reliability, leading to the widespread off-grid terrestrial applications, according to numerous interviewees. For example, the first large, megawatt-scale PV utility plant was designed and built by Sacramento Municipal Utility District in 1983 (Yerkes, 2004).

M2: Refined measurement / testing standards for PV modules

Despite the increasing research activities in private sectors to meet the growing market needs for terrestrial PV applications, reference model and detailed procedures developed by NASA were not publicly available, making it difficult for the wider community to replicate reference spectrum in their research, noted an interviewee. As this hampered accurate performance of R&D and effective sharing of its results in a wider group of researchers, needs for more refined and publicly available standards were identified. As a result, technical committees dedicated to PV were established in SDOs, and works were divided according to their nature and expertise (Ross & Smokler, 1986). A number of interviewees recalled that a steering committee on solar energy was established for coordination and avoidance of duplicative efforts in standardisation among American Society for Testing and Materials (ASTM), Institute of Electrical and Electronics Engineers (IEEE), and Underwriters Laboratory (UL). An interviewee also highlighted that such efforts for coordination and division of labour led by government and public organisations were helpful in the beginning, as PV was an emerging industry where stakeholders had only fragmented understanding about the market, so industry was not strong enough to drive standardisation activities themselves.

Based on their expertise in test methods and specifications, ASTM E44 – which was mainly consisted of researchers at the time – developed a number of early measurement and testing standards for PV. ASTM E891 and ASTM E892 were published in 1982, presenting terrestrial direct normal solar spectral irradiance tables with more refined data and strong technical basis; this 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 ASTM E948 documented more detailed and clarified test conditions and procedures of measuring cell efficiency, so that performance can be measured accurately and consistently. In addition, a series of standard methods for calibration and characterisation of reference cells (ASTM E1039, ASTM E1125, ASTM E1144, and ASTM E1362) were published from 1985 to 1990, ensuring accuracy, stability, and reliability of efficiency results, noted another interviewee. Although these ASTM standards are solution-describing standards outlining procedures without setting criteria (unlike JPL specifications), they facilitate research activities of generic PV technology, by providing a level playing field where everyone can be measured against and guiding research directions for more effective technology improvement, according to an interviewee. Moreover, they supported the development of measurement techniques and testing equipment, which are important infratechnologies themselves. Because of such highly scientific and research-intensive characteristics, researchers from laboratories such as NREL actively participated in the development of these measurement and testing standards, by providing invaluable resources and experiences in characterising and testing PV cells and modules (McConnell, 2006). Such development of infratechnologies allowed enhanced traceability, leading to significant improvements in cell performances in 1980s, despite the decreased public research funding in favour of nuclear energy over PV during this period (Surek, 2003).

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

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

C1: Compatibility / interface standard for residential PV systems

Compatibility standard which describes interface construction techniques and operating procedures for connecting PV systems with the utility was thus needed, in order to give confidence to utility companies, noted an interviewee. With their expertise in electrical and electronics systems, IEEE SCC21 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; interviewees highlighted that this anticipatory standard was a prerequisite for PV systems to be integrated in larger grid systems, leading to the commercialisation of on-grid, residential solar power system in early 1990s.

V1: Variety-reduction standard for wafer size

An interviewee recalled that until 1980s, manufacturers often used wafers designed for computer chip manufacturing, which was available from semiconductor industry at the time. With the demonstration of the potential for grid-connected systems and increased government supports in late 1980s, the PV market of significant size had been established, leading to manufacturers' experiments with the wafer designed specifically for PV modules (Räuber, 2003). By early 1990s, 125mm wafer – used by Siemens and Sharp – was selected 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 noted that the standard 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 across the world, demands for internationally accepted quality standards arose by manufacturers so that they could sell their products worldwide, noted multiple interviewees. International Electrotechnical Commission (IEC) thus developed IEC 61215 in 1993, defining specific sequences, conditions, and requirements for the design qualification of PV modules (Arndt & Puto, 2010). As a participatory standard with improvements incorporated as experience is accumulated, this quality standard presented more refined and advanced testing methods by adopting existing national or regional standards, such as those developed by JPL and the European Commission's Joint Research Centre (Treble, 1986). It could thus further increase consumer confidence and gain wider market acceptance, leading to the wide deployment of PV products and systems (Ossenbrink, Müllejans, Kenny, & Dunlop, 2012). In addition, a number of interviewees mentioned that it facilitated manufacturers' experiments with PV module designs, in attempts to identify reliable designs that could be produced with low costs and still pass the tests. It is 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 in order to gain competitive advantages through standardisation, according to multiple interviewees.

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

As the global awareness towards renewable energy increased (as shown by strong policies in Germany and enactment of Kyoto Protocol), the US government initiated a number of government programs – including Million Solar Roofs Project and Renewable Portfolio Standard – to increase the PV market in late 1990s (Colatat et al., 2009; Räuber, 2003). This led to the development of more reliable and cost effective PV systems, increasing the potential of PV as an alternative source of energy; however, 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, which are called BOS – also had to be ensured, to increase confidence of 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 – i.e. an industry supported group addressing the installation safety of PV systems – in order to ensure more harmonised standardisation among different organisations (Bower, 1997). According to interviewees, this national standard was a major milestone in the US, as it resulted in the wide adoption of on-grid PV applications and systems, by increasing reliability and consumer confidence for larger PV systems. Data also supports that the off-grid dominated PV industry started to generate more electricity from on-grid systems since late 1990s (Mints, 2013). An interviewee added that a lot of its contents were later borrowed to develop IEC 62109, an international standard for the safety and reliability of BOS used in PV power systems.

C2: Compatibility / interface standard for PV power systems

For PV systems to be adopted in complex power systems, compatibility standards that establish successful linkages between distributed resources – such as PV and wind – with electric power systems were needed by utility companies and system developers (Basso, 2009). IEEE 1547 was thus developed by a group of researchers as well as utility companies in 2003, replacing previously developed IEEE 929 which covered intermediate PV systems only (Ji, 2009). A number of 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. Some interviewees added that such issue of interoperability and communication is becoming more important with the widespread of PV, as utilities would need to communicate with them to better control the overall power system.

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 for more efficient productions. After numerous engineering studies and experiments by manufacturers to find out the optimal design, standardised designs for various dimensions – such as spaces between cells, number of cells in arrays, and thickness of panels – emerged in the market, noted an interviewee from the industry. He added that such responsive standards led to more economic production for manufacturers, by allowing them to use standardised equipment for certain module designs.

3.4 Emergence of smart grid (2006~2016)

In late 2000s, the PV industry experienced not only massive growth in terms of production and market, but also the advent of smart grid, which is an advanced power grid integrating many varieties of ICT with the existing power-delivery infrastructure. Such trends called for various standardisation activities led by diverse group of stakeholders involved.

V3: Variety-reduction standards for mass production

According to multiple interviewees, there were urgent needs for standards related to production processes, in order to not only improve communications between users and suppliers of PV manufacturing equipment, materials, and services, but also reduce variability in manufacturing processes to achieve economies of scale. Although existing standards developed by Semiconductor Equipment and Materials International (SEMI, a global trade association representing the semiconductor equipment and materials companies) were somewhat relevant, they were not entirely suitable for material processing required by PV manufacturers, noted another interviewee. Hence, a technical committee consisting of PV equipment and materials companies was established in SEMI, in order to modify existing standards and develop new guidelines for PV-related process equipment, materials, or components (SEMI, 2015). These standards developed by a consortium of supplier networks resulted in not only lower production costs, but also increased efficiency and consistency for process control, by improving traceability and optimising value-adding processes, according to multiple interviewees. An interviewee highlighted that such traceability is important for the development of a big industry, as most of technology improvement is done in regular production line rather than laboratory R&D. SEMI standards thus 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

As the issue of interoperability between PV systems and the larger power grid became more significant, IEEE 2030 was developed in 2011, in order to further realise greater implementation of ICT for enhanced integration of various distributed energy generators with the grid, noted an interviewee. In addition to advanced communication provided by IEEE 1547, IEEE 2030 supports information exchanges where data and knowledge flows are implemented through interfaces (Basso, 2014). As it is the first systems level standard for the emerging area of smart grid, it also included definitions of key terminology used in the industry; since smart grid is an interdisciplinary area where people with different expertise and backgrounds need to work together, agreeing on common language from the beginning was important to facilitate communications among stakeholders across all tiers of the supply network, according to an interviewee. He also noted that as smart grid is becoming more complex and divergent, more of such interface standards involving a great number of stakeholders will be needed, in order to achieve the successful interconnection of PV technologies with various other technologies and systems.

Q4: Quality / reliability standard for PV production systems

As new PV manufacturers with mass production capacity have been recently emerging, there are increasing concerns among the PV community regarding quality management systems of mass manufacturing processes, according to multiple interviewees. Although qualification standards ensure the quality of PV module designs, they do not guarantee that high quality products are consistently manufactured in large factories. Therefore, IEC TS 62941 is recently published in 2016, providing guidelines for increased confidence in PV module design qualification and type approval (IEC, 2016). It specifies quality management systems required for manufacturers to increase the confidence that the production modules will continue to meet the quality implied by passing the module qualification tests, i.e. IEC 61215 for crystalline silicon, IEC 61646 for thin films, or IEC 62108 for concentrators (Wohlgemuth, 2014). Although there were identified needs for such information of quality controls to increase consumer confidence in mass manufacturing in China – which may allow further production growth and cost reductions –, there was a lack of consensus on technical details among members of the committee; it was thus published as TS, which may become IS when full consensus is achieved, noted an interviewee. Another interviewee highlighted that even though TS usually does not lag behind IS in terms of technical details and completeness, it allows greater flexibility until more data and information are gathered so that the industry gets familiar to make better decisions.

4. Discussion

4.1 Demonstration and minor revision of the framework

The case study illustrates how the framework in Figure 1 can be used for more systematic and comprehensive analyses of complex dynamics between innovation and standardisation of PV technology. As these dynamics are context-dependent, the holistic and integrative approach of a roadmap-based framework is useful to have a broad picture of various perspectives on how standardisation shapes the process of technological development and diffusion, facilitating overall innovation systems. It does so by not only capturing all important aspects of standardisation in the context of technological innovation – *what*, *why*, *when*, *how*, and *who* –, but also providing more careful articulation and characterisation of each of these dimensions. Although all dimensions and their sub-categories identified by Ho & O'Sullivan (2015a) are proved to be critical for such multi-dimensional approach to standardisation, the case study suggests that the framework can be further improved by incorporating the following issues.

'What' innovation elements are relevant to standardisation

Multiple interviewees noted that although general activities of the industry outside the innovation system in question do not directly influence standardisation, they still provide important contexts by serving motivations or backgrounds of other innovation activities. For example, space race and increased attention to energy security were important motivations for PV research; international landscape such as policies in Germany and growth 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 of '*what*'.

In addition to federal government policies and regulations, codes adopted by local state governments are found to have significant influences on standardisation activities. A number of interviewees noted that changes in NEC Article 690 often triggered revision of existing standards (e.g. UL 1741 to include ground fault protection) or even development of new ones (e.g. UL 1699B outlining investigation for PV DC arc-fault circuit protection). Hence, it is appropriate in 'policy & regulation' category to also consider such regionally enforced regulations and codes which have significant impacts on standardisation activities.

'Who' is leading and involved in standardisation

As standardisation activities are mainly driven by the industry rather than government in the US, non-profit SDOs (e.g. ASTM) and professional engineering or scientific associations (e.g. IEEE) also develop national standards. Hence, it may be more appropriate to distinguish between these Sectoral or Specialised Standards Organisations (SSOs, professional or specialist organisations comprised of organisations or individuals in particular business sectors or professional disciplines) and Formal Standards Organisations (FSOs, SDOs operating through national representation formally recognised by government authority), rather than categorising them by national, multinational, and international SDOs (Hatto, 2013).

In addition to companies from the PV industry (including manufacturers and suppliers), users and consumers of PV products and systems (such as investors, installers, project developers, and government) are also greatly concerned in standardisation to ensure high quality, reliability, and safety of products. Multiple interviewees noted that it is important to reflect interests and perspectives of such users, as they provide useful perspectives from installation and end-use of products and systems. As representatives of small companies who don't have enough resources to devote, trade associations are also important participants of standardisation activities, according to an interviewee. Moreover, a number of interviewees highlighted the significant role of individual consultants who, based on their long experiences in the PV industry as an employee, now work independently as a specialist in PV standardisation. By participating in multiple SDOs, they may provide a broader perspective on standardisation activities of the overall industry, noted the interviewees.

4.2 Further insights into dynamics between standardisation and innovation

The case study also illustrates a number of interesting trends and patterns of how dimensions of standardisation evolve and interact with each other throughout the PV innovation, reflecting changes in innovation systems. Such trends are due to the evolving emphasis on types of technologies and innovation activities across different stages of innovation, requiring different standardisations involving various stakeholders; these are discussed as below.

'What' innovation elements are relevant to standardisation

There were more technology-supporting standards developed in early stages of innovation where basic scientific research dominated; as PV systems developed and market expanded, first production-facilitating standards, then market-enabling standards were mainly developed. Nevertheless, interviewees noted that as new technologies are continuously being introduced, new technology-supporting standards appear mostly in related technological areas or different materials, other than generic PV technology that is basis of current PV products and systems.

'Why' standards are needed

Although standards playing the same roles are needed at different phases of PV innovation associated with different categories of technology, there is a general trend that standards with particular roles and functions dominated at certain stages of the innovation journey: measurement / testing standards in early PV technology development, quality / reliability standards with the introduction and demonstration of applications, and compatibility / interface standards with the widespread of larger systems. According to a number of interviewees, similar trends could be observed in not only other countries that were the main players of PV history, but also different types of PV technology, such as concentrators.

'When' to be standardised

While many standards were – either perfectly or partially – participatory standards, evolving and being refined with technology improvements, some standards with particular roles tended to be of different types. Many variety-reduction standards, especially regarding certain dimensions or characteristics of products, were responsive standards, as they were defined after their performance or success had been demonstrated. On the other hand, compatibility / interface standards were anticipatory standards, since they had to be defined in advance to ensure that different products and systems can be connected and interoperable to each other.

'How' to standardise

It is interesting to note that all quality / reliability standards illustrated in the case study were both performance-based and solution-describing standards, specifying both desired outcomes or performance criteria and how to perform test procedures to assess these performances.

'Who' is leading and involved in standardisation

In early days of PV, standards were mostly developed by researchers from national laboratories or academia, with resources supported by government to perform research in the emerging technology with high risks. As potentials of PV applications were demonstrated, manufacturers and other companies – including suppliers and investors – also participated;

system-related stakeholders – such as utilities, system integrators, and installers – 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.

5. Conclusion

The historical case study of PV technology is carried out, in order to verify the framework developed by Ho & O'Sullivan (2015a) for systematic analyses of standardisation (shown in Figure 1). Capturing five key dimensions of standardisation – '*what'* elements are relevant to standardisation, '*why'* standards are needed, '*when'* to be standardised, '*how'* to standardise, and '*who'* is leading and involved in standardisation – in a coherent and integrated way, this roadmap-based framework is proved to be more advanced than existing conceptual models in two main ways. It provides a more holistic and comprehensive perspective of overall dynamics between standardisation and innovation; it also provides detailed characterisation of important dimensions of standardisation in the context of innovation. Through the multi-dimensional analysis of PV history, the case study effectively shows how standardisation evolves across different stages of innovation journey, reflecting changes in technological and industrial systems. As there are significant shifts on types of technologies and innovation activities across different phases of innovation, different types of standards in terms of their roles and associated innovation elements are required by different stakeholders involved. Changes of emphases in dimensions of standardisation and their categories are thus inevitable, reflecting evolutions of innovation systems as technology develops and industry matures.

Such analyses not only enhance previous theoretical works by increasing our understandings of standardisation dynamics grounded in case studies, but also provide practical insights that standardisation may be useful indicators of changes in technological 'paradigms', as claimed by Metcalfe & Miles (1994). As there appear to be close relations between them, multi-dimensional analyses of standardisation may provide greater insights into dynamics and transitions of technological innovation systems, helping the community make more informed decisions when developing innovation strategies. For example, key characteristics and patterns of standardisation activities – especially when considered in an integrative way – 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 not only make appropriate reviews or strategic decisions in a timely manner, but also guide how various actors should coordinate with each other at each stage, supporting innovation more effectively. It would be interesting to further examine such issues regarding potential roles of standardisation as defining or indicating features of technological paradigms and innovation systems.

Another managerial implication is that the proposed framework may also be used as a practical tool for helping standards organisations and policymakers anticipate future standards needs and develop relevant standardisation strategies. Such future-oriented analyses are supported not only by more comprehensive understandings of complex dynamics between standardisation and innovation, but also due to the basic function of roadmapping as a foresight tool, where various stakeholders are brought together to make strategic decisions to achieve a common vision. Demonstrating the importance of five key dimensions and their sub-categories for understanding complex dynamics between standardisation and innovation, the case study suggests that all these dimensions need to be appropriately considered for effective standardisation foresight. It also provides additional insights to be incorporated, leading to minor revisions of the framework with more careful articulation and characterisation of each dimension. These include addition of industry environment and refinement of policy & regulation in '*what*', addition of users and consultants in '*who*' is involved in standardisation, and refinement of '*who*' is leading standardisation; as these are relatively marginal changes, the improved framework is not reproduced here. Future research may involve more case studies to test the framework in a variety of technological domains, exploring dynamics between standardisation and innovation in greater details. They may lead to further articulation and detailed characterisation of various issues regarding standardisation in the context of innovation, such as processes of variation and selection, as identified in existing literature adopting an evolutionary perspective (e.g. Metcalfe & Miles 1994).

Last but not least, there is evidence that demands for such use of the proposed framework for standardisation foresight will significantly increase in the future. By providing an overall view of complex dynamics of standardisation from various perspectives, the roadmap-based framework is particularly useful for gathering the growing number of stakeholders, who have different interests and make different contributions, but have a common goal of supporting the overall innovation system through standardisation. As modern technologies are becoming more complex, interdisciplinary, and fast-evolving at the same time, such efforts for collaboration among experts from different backgrounds and disciplines are becoming more significant, in order to meet increasing demands for timely and efficient development of highly complex standards. In addition, as more standards developed by different SDOs are being interrelated with each other (e.g. IEEE 929 and UL 1741, IEC 61215 and IEC TS 62941 as shown in the case study), the roadmap-based framework would make it easier to observe such interactions and linkages, helping achieve coherence and harmonisation of various standardisation activities. Since the framework is flexible and scalable – as demonstrated from the case study where particular perspectives in certain periods of time are zoomed in for exploring details of dynamics between standardisation and innovation – it is also possible to collate individual roadmaps developed by different SDOs and integrate them for a broader standardisation plan of the overall industry.

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