Standardisation framework to enable complex technological innovations: The case of photovoltaic technology

Abstract[1]

Strategic standardisation is becoming increasingly challenging due to high levels of complexity, interdisciplinarity, and systems nature of modern technologies. This paper develops a standardisation mapping framework for systematic and comprehensive analyses of how standardisation supports innovation, by integrating key 'dimensions of standardisation' addressed in existing conceptual models and related literature. A longitudinal case study of photovoltaic technology highlights evolving dynamics of these dimensions over multiple technology lifecycles, thus demonstrating the importance of such holistic and integrative approach. Based on a widely-used foresight tool, the framework can be used to help decision-makers develop more coherent, long-term, and system-wide strategies for standardisation.

Keywords: standard; technological innovation; complex system; roadmapping; foresight

JEL classification: L15, O32, O38

Abbreviations used: ASTM (American Society for Testing and Materials), FSO (Formal Standards Organisation), IEC (International Electrotechnical Commission), IEEE (Institute of Electrical and Electronics Engineers), NREL (National Renewable Energy Laboratory), SDO (Standards Developing Organisation), SEMI (Semiconductor Equipment and Materials International), SSO (Sectoral or Specialised Standards Organisations), UL (Underwriters Laboratory)

1. Introduction

There has been growing interest in recent years in strategic management and foresight of standardisation activities to support technological innovation (European Commission 2011; Ho & O'Sullivan 2017). This is driven, in part, by the increased complexity of technological systems, and informed by the innovation systems approach, which highlights technical standards as important institutions in innovation systems (Edquist & Johnson 1997; Lundvall 1995; Van de Ven 1993). Standardisation – defined as "[the] activity of establishing and recording a limited set of solutions… intending and expecting that these solutions will be repeatedly or continuously used… by a substantial number of the parties for whom they are meant" (de Vries 1999 p. 19) – can support innovation in a variety of ways. 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; Blind & Gauch 2009; Swann 2010; Tassey 2000). However, untimely or inappropriate standards may also have negative impacts on innovation, such as risks of monopoly and problems of lock-ins into inferior standards (Grindley 1995; Swann 2010).

Due to such dual impacts of standardisation, strategic planning and management of standards development is critical in supporting innovation. This can, however, be highly challenging, as the effects of standardisation on innovation vary significantly depending on diverse factors. In particular, there is a range of types and forms of standards, developed by a variety of stakeholders coordinating in various modes, and playing different roles in technological innovation (Blind & Gauch 2009; Sherif 2001; Tassey 2015). Moreover, these multiple factors evolve through different stages of technology lifecycles, often with growing levels of systems complexity, as technologies mature and industries develop over time. Despite such complex dynamics, existing frameworks address only certain aspects of these dynamics, from relatively narrow theoretical or particular disciplinary perspectives (Narayanan & Chen 2012). Consequently, they can only explain the variety and complexity associated with standardisation within particular phases and contexts of innovation.

Challenges with strategic management of standardisation are becoming more significant, as modern technologies are increasingly complex, interdisciplinary, and systems-like in nature, requiring coordination of various innovation stakeholders from different domains (Funk 2011; Ho & O'Sullivan 2017; Tassey 2015). Because traditional market-driven, sector-specific, and reactive approaches are no longer effective in such complex and dynamic environments (European Commission 2011), systematic and future-oriented analyses are needed to effectively support innovation, by considering various issues of standardisation in a holistic and dynamic way (Scapolo et al. 2013). Therefore, governments and SDOs across the world are increasingly adopting strategic foresight tools and processes (e.g., roadmapping) to anticipate evolving standardisation needs and develop relevant strategies in various areas of complex technological systems (e.g., Smart Grid (NIST 2012) and electromobility (NPE 2012)).

In this regard, further research is needed to provide more comprehensive and systematic guidance in developing standardisation strategies in support of such complex innovation systems (e.g., Blind 2016; Featherston et al. 2016). Integrative studies incorporating multiple perspectives and reconciling various approaches are particularly encouraged, as existing literature lack a holistic and systemic view of standardisation in broad innovation systems (Branscomb & Kahin 1995; Narayanan & Chen 2012). While den Uijl (2015) suggests an integrative framework of elements to consider when developing corporate strategies for particular market-based standardisation, it is insufficient to guide broader stakeholders (e.g., SDOs, trade associations, or even governments) develop coherent, long-term, and system-wide strategies for a group of standards over multiple technology lifecycles.

In order to fill this gap, this paper develops a practical, roadmap-based 'standardisation mapping framework' with particular focus on technical standards, for effective standardisation to support complex innovation systems. Integrating insights from different conceptual models as well as complementary literature, it systematically incorporates various key 'dimensions of standardisation' (i.e., broad categories of elements and issues that need to be accounted for strategic standardisation), thus allowing holistic and systematic investigation of all strategic decisions relevant to standardisation. A longitudinal, in-depth historical case study of photovoltaic (PV) technology is then carried out. Illustrating that evolving, interdependent dynamics of innovation and standardisation across multiple technology lifecycles (with varying levels of systems complexity) can only be fully understood by acknowledging the full set of these dimensions, it demonstrates needs for an integrated perspective of the proposed framework. Hence, the case study suggests the framework's usability, not only as a practical foresight tool, but also as a platform for systematic analyses of how standardisation supports innovation. The paper finally reflects on its implications for academic theory and policy practice, before suggesting areas of future research.

2. Literature review

2.1. Existing frameworks for standardisation and innovation

Despite the significant volume of research on standardisation, previous academic research is limited to relatively narrow theoretical and disciplinary perspectives, resulting in fragmented bodies of literature providing only partial pictures (Branscomb & Kahin 1995; Narayanan & Chen 2012). A few scholarly attempts have been made to establish frameworks for detailed characterisation of how standardisation supports technological innovation, but these have different focus of analyses, and are not fully consistent or complete. Tassey's (2000) static framework differentiates various forms of knowledge embodied in standards relevant to different types of technologies (e.g., generic technologies, infratechnologies) and other innovation activities (e.g., production, market development), but does not address how standardisation effort evolves over technology and industry lifecycles. Sherif (2001) does present a framework relating different types of standards emerging at different phases of technology lifecycles (i.e., anticipatory, participatory, and responsive standards), but focuses on committee-based, interface standards relevant to Information and Communications Technology (ICT) only. A more recent framework by Blind & Gauch (2009) provides important clarity on the economic functions of standards applicable in more general contexts, but focuses on the development of a single technology application, without accounting for potential growing levels of systems complexity as technology-based applications mature and industry evolves.

Although these individual conceptual models allow greater understanding of complex dynamics between standardisation and innovation, they highlight different characteristics and issues of these dynamics (see Table 1), by focusing on different units of analyses (i.e. those of industry, technology, and research processes) and adopting particular theoretical lenses. Existing frameworks thus lack integrative and systemic perspectives required to analyse impacts of standardisation on broad innovation systems undergoing multiple technology lifecycles with varying levels of systems complexity. Furthermore, these studies offer somewhat limited empirical evidence, providing conceptual models only.

Table 1. Focus of analyses and various issues addressed in existing frameworks

	Tassey (2000)	**Sherif (2001)**	**Blind & Gauch (2009)**
Focus of analyses	Technological and innovation activities in industrial systems	Technology lifecycles in the context of ICT	Research and innovation processes
Technology elements/systems relevant to standardisation	Science base Generic technologies Proprietary technologies Infratechnologies	Product systems Application systems Production systems Service systems	Pure basic research Oriented basic research Applied research
Other aspects of innovation relevant to standardisation	Strategic planning Entrepreneurial activity Production Risk reduction Market development		Experimental development Market diffusion
Roles / functions (types) of standardisation	Materials characteristics Measurement & test methods Process & quality control Interface standards Transaction standards	Interface standards - Reference standards - Similarity standards - Compatibility standards - Flexibility standards Performance & quality standards	Semantic standards Measurement & testing standards Interface standards Compatibility standards Quality standards Variety-reducing standards
Timing [Sequencing] of standardisation	[framed in linear cycle of technology R&D only]	Anticipatory standards Participatory standards Responsive standards	[framed in linear cycle of technology R&D only]

Given the complex, evolving nature modern technological innovation systems, effective standardisation strategy development requires an integrated framework, incorporating all relevant issues captured in the different conceptual models; it can then allow more systematic, longer-term, and system-wide analyses of standardisation in support of complex technological innovation systems (den Uijl 2015).

Although there have been a few academic efforts to such integrative and systematic analyses, none of them offer any clear approaches to integrating the different perspectives of Tassey (2000), Sherif (2001), and Blind & Gauch (2009). While den Uijl's (2015) integrative framework particularly focuses on market-based standardisation only, both Egyedi (1996) and Garcia et al. (2005) pay greater attention to social and organisational aspects of standardisation with limited attention to the variety of technical details, which present increasing challenges in complex technological innovation systems (as previously discussed). In this context, we explore the practical approach of strategic roadmapping (as adopted by Featherston et al. 2016) as a potentially useful basis for developing an integrative framework.

2.2. Roadmap-based framework for systematic and future-oriented analyses of standardisation

Originally developed as a foresight tool, strategic roadmapping has been widely used to support technology and innovation planning, by providing a structured platform for gathering collective intelligence regarding future strategies (Groenveld 2007; Phaal & Muller 2009). Adopting its basic principles and structures, Featherston et al. (2016) proposed a roadmap-based framework that helps anticipate where standards may be needed and develop relevant strategies to support innovation. This was done by integrating insights from existing literature on innovation (e.g., Van de Ven, 1993; Edquist and Johnson, 1997) as well as standardisation (e.g., Allen and Sriram, 2000; Swann, 2010) within a generic roadmapping framework.

In particular, the roadmap-based framework can be used as a practical tool for developing standardisation strategies, by exploring relationships between a variety of relevant innovation activities and linking them with associated standardisation opportunities (Featherston et al. 2016). It also provides a useful platform of coordinated engagements for strategic planning and management of standardisation, which is intrinsically the consensus-building activities of various stakeholders involved (Wiegmann et al. 2017). Recognising such advantages, an increasing number of foresight analyses based on the roadmapping approach are recently being carried out for strategic management and planning of standardisation, particularly in complex technological systems with high public interests (Ho & O'Sullivan 2017; NIST 2012; NPE 2012).

In addition to its practical uses as a foresight tool for future strategies, the roadmap-based framework can also be used as an analytic tool for observing complex dynamics of how standardisation supports technological innovation in a more systematic way. By extending the time axis to the past, systemic perspectives of the roadmapping concept can be applied to historical contexts, providing a structured canvas for investigating complex and evolving dynamics between standardisation and innovation (Phaal & Muller 2009; Phaal et al. 2011). Because this structure allows for the visualisation of several lifecycles (including those of industry, technology, and research processes) at once, it helps increase the understanding of their complex dynamics in a coherent and holistic way (Routley et al. 2013). In the context of standardisation, an integrative framework of roadmapping may provide a platform for comprehensive and systematic analyses of how different aspects and varieties of standardisation influence complex technological innovation systems undergoing multiple lifecycles with varying levels of systems complexity.

Although the previous work by Featherston et al. (2016) offers a 'proof of principle' for such potential utility of the roadmap-based framework (as both a practical tool and an analytical platform), further work is required to develop a framework that is both practical and well grounded in theory. First, the list of dimensions included in the Featherston et al.'s (2016) framework is not comprehensive, missing important tactical issues, particularly those highlighted in recent literature (such as modes of coordination and types of SDOs engaged, Wiegmann et al. 2017). Second, capturing only main actors associated with particular technology and innovation activities, the framework does not fully account for diverse sets of stakeholders involved in standardisation. Last but not least, although the case for the framework is compelling, it is not yet fully grounded in theory.

Such limitations are partly demonstrated in their case studies: limited to snapshots at certain phases of innovation, their case studies are also insufficient to show potentials of the framework in supporting long-term and system-wide analyses of standardisation through evolving technology lifecycles. In addition, their analyses are based on limited sources of documents only, potentially limiting insights or delivering findings constrained by existing conceptualisations of the role of standardisation.

In order to address such limitations, a more integrative framework (building upon the existing roadmap-based framework by Featherston et al. 2016), but accounting for all key dimensions of standardisation, strongly grounded on theory, is needed. A longitudinal, in-depth case study based on primary data is also needed to demonstrate the framework's ability to explore evolving dynamics of these issues over multiple technology lifecycles of complex innovation systems.

3. Standardisation mapping framework

3.1. Dimensions of standardisation

In order to develop an integrative framework for systematic analyses of standardisation, we first review existing conceptual models of standardisation to identify and categorise relevant elements to be incorporated. Although a number of scholars attempted to develop consistent and systematic categorisations of standard-relevant issues, none of them are adequate for the purpose of exploring standardisation dynamics in complex technological innovation through multiple technology lifecycles. For example, de Vries (1998, 2005) presents a list of various classifications of standardisation as well as a dimensional matrix of relevant topics, but they neither place much emphases on innovation, nor properly account for technological details, which present particular challenges in recent years. Sherif (2001) presents a list of six important questions that help address strategic and tactical issues relevant to standardisation; however, focusing on interface standards in ICT only, most of them are contextual factors rather than key dimensions influencing innovation. Although Egyedi & Ortt (2017) suggest a classification that generally applies to broader contexts, it pays great attentions to standards' roles and functions on innovation, not taking into account other characteristics and issues required for understanding their dynamics in complex technological systems.

In order to identify all relevant aspects of interdependent dynamics between standardisation and innovation – in particular, key 'dimensions of standardisation' – a systematic review of both academic (i.e., 'white') and practice (i.e., 'grey') literature on standardisation has been carried out. The review of 'grey literature' particularly increased the practical relevance and impact of the research, as it provided diverse and heterogeneous body of public material outside traditional academic literature (Adams et al. 2017), complementing and supplementing the previous framework proposed by Featherston et al. (2016). For a systematic review of such grey literature, several tactics suggested by Adams et al. (2017) have been adopted, such as: being guided by field experts in identifying sources for and evaluating literature; using quality criteria to select and evaluate literature; and including grey literature as supplementary and complementary evidence rather than a competing form. Following the five steps of a systematic review suggested by Denyer & Tranfield (2009), 162 academic articles and 31 practice studies have been identified through iterations of comprehensive search, abstract screening, and evaluation against selection criteria.

Review and analyses of these literature have been guided by key issues of standardisation highlighted in existing literature. In particular, six questions previously adopted by Baskin et al. (1998) (i.e., '*what*', '*why*', '*when*', '*how*', '*who*', and '*where*') can be used as an initial analytical framework. Sherif (2001) further distinguishes between strategic (i.e., '*what*', '*why*', and '*when*') and tactical questions (i.e., '*how*', '*who*', and '*where*'). While strategic questions are principally related to key dimensions addressed in existing frameworks of standardisation (i.e., technology and innovation elements relevant to standardisation, their roles and functions, and timing, see Table 1 for details), tactical questions may address additional important issues suggested by recent literature (e.g., modes of coordination, types of SDOs).

The initial analytical framework thus involves a comprehensive and integrative list of all relevant dimensions of standardisation, drawing together key strategic issues highlighted in different conceptual models with distinct perspectives, as well as complementary tactical issues suggested by other (practice) literature. Details of each of these dimensions (guided by the six questions) are discussed in the following subsections, along with exemplar categories of each dimension presented in Table 2 (details summarised in tables in Appendix). It is to be noted that these tables list only selected examples typically discussed in existing literature, while detailed categories and exact labels need to be customised by users of the framework to accommodate particular circumstances being investigated, reflecting language and terminology used by the community.

3.1.1. '*What*' innovation activities are relevant to standardisation

Depending on '*what*' technology and innovation activities are relevant, standards have different strategic and marketplace roles, and different rationales for and the processes by which they are set (Tassey, 2000; 2015). Broadly categorised into technology, production, and market-related activities, they may be further refined using established categories adopted in generic roadmapping architecture (e.g., Phaal and Muller, 2009), as well as economic literature on standardisation (e.g., Tassey, 2000). While customisable to accommodate particular characteristics of technological systems under consideration, examples of key technology and innovation activities relevant to standardisation, as discussed in literature, are listed in Table 2 (further details are provided in Table A.1 of Appendix). It is to be noted that they are closely related to, but different from, technologies that are actually being standardised (which are sometimes referred to as 'subject matters' or 'interfaces' to be standardised, as in Sherif, 2001). For example, while measurement standards (which will be described in the next section) in semiconductor industry are essential for R&D activities to achieve high-density electronic functions of chips, and thus relevant innovation activities, they actually standardise methods and techniques of operating equipment used to measure distances between individual atoms

(Tassey, 2000).

3.1.2. '*Why*' standardisation is needed

Depending on the type of technical knowledge they codify and transfer between various innovation activities, standardisation perform various different roles and functions (Ho & O'Sullivan 2017). Many academic and practice literature have identified various types and choices of standards, according to their strategic purposes, functionalities, or economic problems they solve (i.e., '*why*', e.g., David, 1987; Sivan, 1999; Hatto, 2013). Summarising these literature, Table 2 presents the list of five different types of standards commonly used in technology-intensive systems, providing different roles and functions (details provided in Table A.2 of Appendix).

3.1.3. '*When*' to be standardised

The issue of '*when*' to be standardised is a acritical issue, as standards need to be developed and implemented at the right time to meet intended roles and functions. A standard that is imposed too early hinders diversity and precludes entrepreneurial experiences, closing opportunities for further innovation; whereas a standard that comes along too late may not only retard achieving economies of scale for new market development, but also result in market confusion, both of which are detrimental to innovation (Foray 1998; Grindley 1995).

In addition to the issue of real-time, several conceptual models (including Sherif 2001) provide useful strategic information regarding the timing of standardisation relative to technology lifecycles. Categorised as anticipatory, participatory, or responsive standards, they may play different roles and functions, and be associated with different categories of technological systems (see Table A.3 in Appendix for details).

3.1.4. '*How*' to standardise

Various types of standard deliverables with different levels of flexibility exist, depending on the maturity of topic and the level of consensus achieved (Hatto 2013). Standards are also developed in various different formats (e.g., specifications, test methods, guidelines) (Sivan 1999); different organisations use different terms and definitions, but they may broadly fall into either performance or solution-describing standards. In addition, as these strategic choices partly differ in terms of development and approval processes as well as SDOs' policies, the coordination mechanisms of standardisation is an important issue of '*how*' to standardise. Broadly categorised into committee-based, market-based, and government-based standardisation, different 'modes of coordination' imply fundamentally different relationships between actors involved in standardisation (i.e., cooperation, competition, or hierarchy, respectively) (Wiegmann et al. 2017). These are summarised in Table 2 (with details in Table A.4 in Appendix), along with a list of exemplar categories, as typically discussed in literature.

3.1.5. '*Where*' standards are developed

There are various avenues of standardisation (i.e., organisations leading standardisation) depending on modes of coordination; committee-based mode takes place in committees of SDOs, consortia, professional associations, or research initiatives; market-based mode takes place in the market where solutions first developed as industry or proprietary standards are diffused; and government-based mode takes place in governmental bodies developing standards or enforcing their use (Wiegmann et al. 2017). Thus closely related to the issue of '*how*' to standardise, this issue of '*where*' standards are developed is also related to geographical areas, as standardisation systems vary considerably according to historically rooted, and often nationally distinct, institutional trajectories (Zysman 1996). For example, the USA has a highly decentralised, even fragmented, system with individual-oriented professional societies; whereas more coordinated approaches prevail in both European countries (with multiple standards organisations) and Asian countries (with state-run standards-setting institutions) (Tate 2001). Because of such variety, it is impractical to define general typology for the issue of '*where*' in terms of geographical area. In addition, the proposed framework will often be adapted and tailored to suit particular national or regional contexts. Hence, this paper places more attention to broad types of SDOs (listed in Table 2, and details summarised in Table A.5 in Appendix) as generally discussed in literature, whereas the geographical issue is deliberately left out.

3.1.6. '*Who*' is participating in standardisation

A variety of stakeholder groups participate in actual developing and writing processes of standardisation, including consumers, government, industry, consultants, and researchers (Blind 2004; Sivan 1999; de Vries 1999, see Table A.6 in Appendix for details). Although some of them may be further classified according to diverse factors, such as their size, sectors, and roles (as illustrated in some literature, e.g., Sherif et al. 2005), it is not the focus of the current paper to explore in that level of detail, thus left as an area of future research.

3.2. Framework development

Similarly to the framework by Featherston et al. (2016), key strategic dimensions of standardisation (i.e., '*what*', '*why*', and '*when*') can be systematically incorporated into the flexible and adaptable framework of strategic roadmapping, as shown in Fig.1.

The vertical axis captures the issue of '*what*' technology and innovation activities are relevant to standardisation in a layered form, whereas the horizontal axis captures the issue of '*when*' to be standardised in terms of real-time. Key innovation activities and other significant events can thus be recorded in boxes and mapped against the two axes, with linking lines indicating relationships and interplays between them. For any linkages where standards support knowledge diffusion between these activities, a circle with alphabets describing their roles and functions (e.g., Q for quality and compatibility) can be placed, representing the issue of '*why*' standards are needed. Providing useful information on other tactical issues with implications for standardisation, dimensions additionally identified in this research may be included in brackets next to circles (as shown in legends of Fig.1) or in separate tables (as in Table 3 of the case study). They include '*when*' to be standardised relative to technology lifecycle, as well as three tactical dimensions of '*how*' to standardise, '*where*' standards are developed, and '*who*' is leading and participating in standardisation.

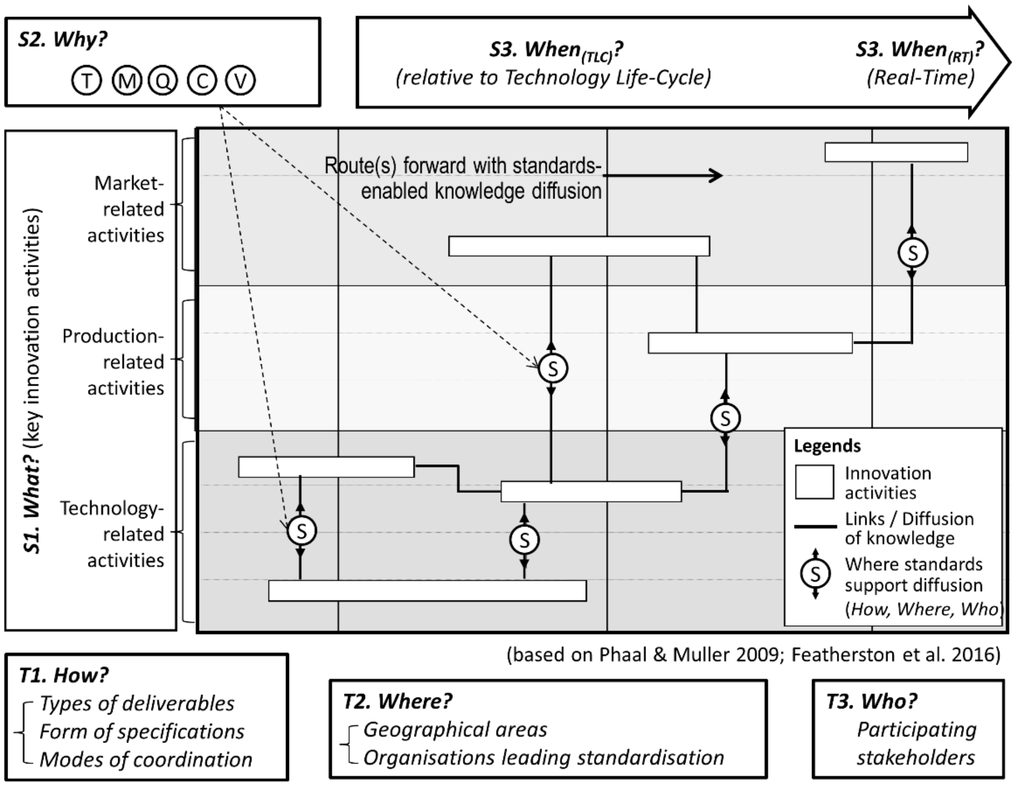

Fig.1 Standardisation mapping framework (see Table 2 for exemplar categories of dimensions)

Table 2 provides examples of strategic and tactical choices to be made for each of the dimensions of standardisation (details of which are summarised in the Appendix). Although these dimensions would need to be adapted and modified to particular circumstances being investigated in any strategic or analytical exercise, the current framework presents an initial platform to begin structured discussions for such configurations, so providing implicit guidance for strategic foresight itself.

Table 2. Exemplar categories for dimensions of standardisation

Dimensions		**Exemplar categories (strategic and tactical choices)**		
S1	'*What*' innovation activities are relevant to standardisation	Market-related activities	Industry environment Policy / regulation Market / customers Business / service Supply network	
		Production-related activities	System Production Product / application	
		Technology-related activities	Proprietary technology Generic / platform technology Infratechnology Science base	
S2	'*Why*' standardisation is needed		Terminology and semantic standards Measurement and characterisation standards Quality and reliability standards Compatibility and interface standards Variety-reduction standards	
S3	'*When*$_{(RT)}$' to be standardised	(in terms of real-time)		
	'*When*$_{(TLC)}$' to be standardised	(relative to technology lifecycles)	Anticipatory standards Participatory standards Responsive standards	
T1	'*How*' to standardise	(types of deliverables)	International Standards (IS) Technical Specifications (TS) Publicly Available Specifications (PAS) International Workshop Agreements (IWA) Technical Reports (TR)	
		(form of specifications)	Performance standards Solution-describing standards	
		(modes of coordination)	Committee-based standardisation Market-based standardisation Government-based standardisation	
T2	'*Where*' standards are developed	(organisations leading standardisation)	(committee-based)	Formal Standards Organisations (FSOs) Sectoral / Specialised Standards Organisations (SSOs) Consortia / Research initiatives
			(market-based)	Individual market actors
			(government-based)	Public agencies Government laboratories
		(geographical areas)		
T3	'*Who*' is participating in standardisation		Consumers Government Industry (companies) Consultants Researchers	

4. Research design and methods

4.1. Longitudinal case study

In order to empirically demonstrate the usability of the framework for systematic and integrative analyses of how standardisation enables technological innovation, a longitudinal case study was carried out. By extending the time axis to include the past, the future-oriented framework could be used to map historical accounts of standardisation and innovation in a way that is compatible with future strategy, as adopted by Phaal *et al.* (2011). Qualitative longitudinal research enabled studying and unfolding complex phenomena, by supporting a holistic understanding of the way diverse factors (i.e., dimensions) come together to determine behaviour (McLeod & Rachel 2009). It is, however, to be noted that the purpose of the case study was not to derive generalised insights about dynamics between these dimensions and relevant strategies, which are impractical in complex and dynamic environments of technological innovation systems. Instead, it aimed to highlight the relevance of these dimensions and the proposed framework's ability to address them, so demonstrating how its holistic and integrative approach allows more systematic, coherent, and long-term analyses of roles of standardisation in complex technological innovation systems.

In particular, a single-case longitudinal study with multiple embedded cases focusing on various phases of the innovation journey (with different main application systems) was conducted, in order to help reduce risks of the holistic case study being conducted at an unduly abstract level (Yin 2009). More details about these embedded cases are discussed in section 5.

4.2. Case study selection

The case of PV technology was selected, because of its various application areas, variety of stakeholder groups, and diverse levels of systems complexity involved, all of which add intricacy and variety to relevant standardisation activities. Critically, the long history of PV development provided rich information to explore diverse issues associated with evolving dimensions of standardisation through various stages and transitions of technology lifecycles. PV technology also provided appropriate contexts for illustrating the proposed framework, as its infrastructural nature and high public interests (due to a series of socio-environmental issues such as oil crisis and climate change) made governments and other public agencies interested in effective standardisation to promote its development and diffusion (Hill 1992). The PV case study was thus suitable for demonstrating how the framework addresses relevant dimensions to be considered for long-term strategic and system-wide analyses of standardisation from holistic and integrative perspectives. The study began by focusing on PV standardisation in the US (i.e., the birthplace of PV technology, where early standardisation is dominated), and then expanded its scope to international contexts with the development of international PV markets.

4.3. Data collection and analyses methods

Given retrospective nature of the research, over 200 documents from various sources – including standard publications, industry trade magazines, and official reports published by governments and research laboratories – were collected. Key events and activities related to innovation and standardisation of PV technology from various perspectives were systematically identified. While many of these documents were available in the public domain, key documents were obtained from the National Renewable Energy Laboratory (NREL) library, which houses archival resources that are not accessible elsewhere. In addition, it should be noted that many policy-related documents published by government departments or other public agencies represented syntheses of a large amount of consulted, verified, and distilled information, so providing rich descriptions and insights into the history of PV technology.

Semi-structured interviews, complemented with the visual mapping process developed by Ford *et al.* (2011), were also carried out with experts in various areas of PV standardisation. The mapping process helped effectively capture interviewees' hidden insights, especially their perspectives on relationships and linkages between innovation and standardisation of PV technology. Interviewees were initially contacted from the list of members in technical committees dedicated to PV technology in major SDOs (i.e., ASTM E44, IEC TC82, IEEE SCC21, and PV Committee in SEMI), then approached using "snowball sampling" (Goodman 1961). A total of 42 experts, selected from a variety of organisations – including national laboratories (14), private companies (13), independent consultants (6), academia (4), governments (3), and standards organisations (2) – across various areas of PV technology, participated in interviews, ensuring the balanced representation of varied perspectives (see Table B.1 in Appendix for their detailed profiles).

Narrative analyses were then used to analyse collected data that are mainly composed of texts from documents and interview transcriptions. Employing elements of storytelling to build the narrative, the sequence of PV innovation and standardisation activities based on temporal ordering of events (Easterby-Smith et al. 2002) was described. They were then visually organised and structured on the standardisation mapping framework (see Fig.2), using the conventions introduced in Section 3.2 (i.e., key standards coded by letters indicating roles and functions, followed by numbers indicating the order of appearance). The narrative and visualisation were also verified by four key interviewees with broad areas of expertise and long experiences in PV standardisation, in order to ensure the validity of collected data.

5. Case study of PV technology and relevant application systems

This section presents the summary of narratives illustrating how various standardisation activities supported the innovation of PV technology through various innovation stage, transitions, and technology lifecycles, by discussing relevant dimensions of these standardisation (i.e., '*what*', '*why*', '*when*', '*how*', '*where*', and '*who*', summarised in Table 3), except the geographical issue of '*where*' standards are developed (as discussed in Section 3.1.5). The study thus demonstrates how the proposed framework can capture evolving dynamics of these dimensions from holistic and integrative perspectives, allowing more coherent, systematic, and long-term analyses of standardisation in complex technological innovation systems.

As shown in Fig.2, the framework has been applied in four embedded cases across different phases of the history of PV technology, divided according to the evolution of its main application systems: (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). The overall innovation journey is also summarised in the central diagram.

5.1. Transition from space applications to terrestrial applications (1976~1985)

Although electricity generated from the PV effect was first observed in 1954, the technology remained in the niche market of space applications due to its high costs (Perlin 2002). Since the oil crisis in the 1970s, PV gained great attentions as an alternative source of energy (Ksenya 2011). Needs for appropriate standards were then identified by a growing number of stakeholders involved in PV research for terrestrial applications (Ross & Smokler 1986). Consequently, two PV Measurement Workshops were organised in late 1970s by the Energy Research and Development Administration (ERDA), resulting in the technical report (NASA TM 73702) which presented the first set of consensus-based (but led by governmental bodies) standards (NASA 1977). According to an interviewee, nearly 60 people from all sectors of the PV community participated in workshops, many of whom were researchers from government laboratories, as they were more experienced in this emerging technology and its early niche applications.

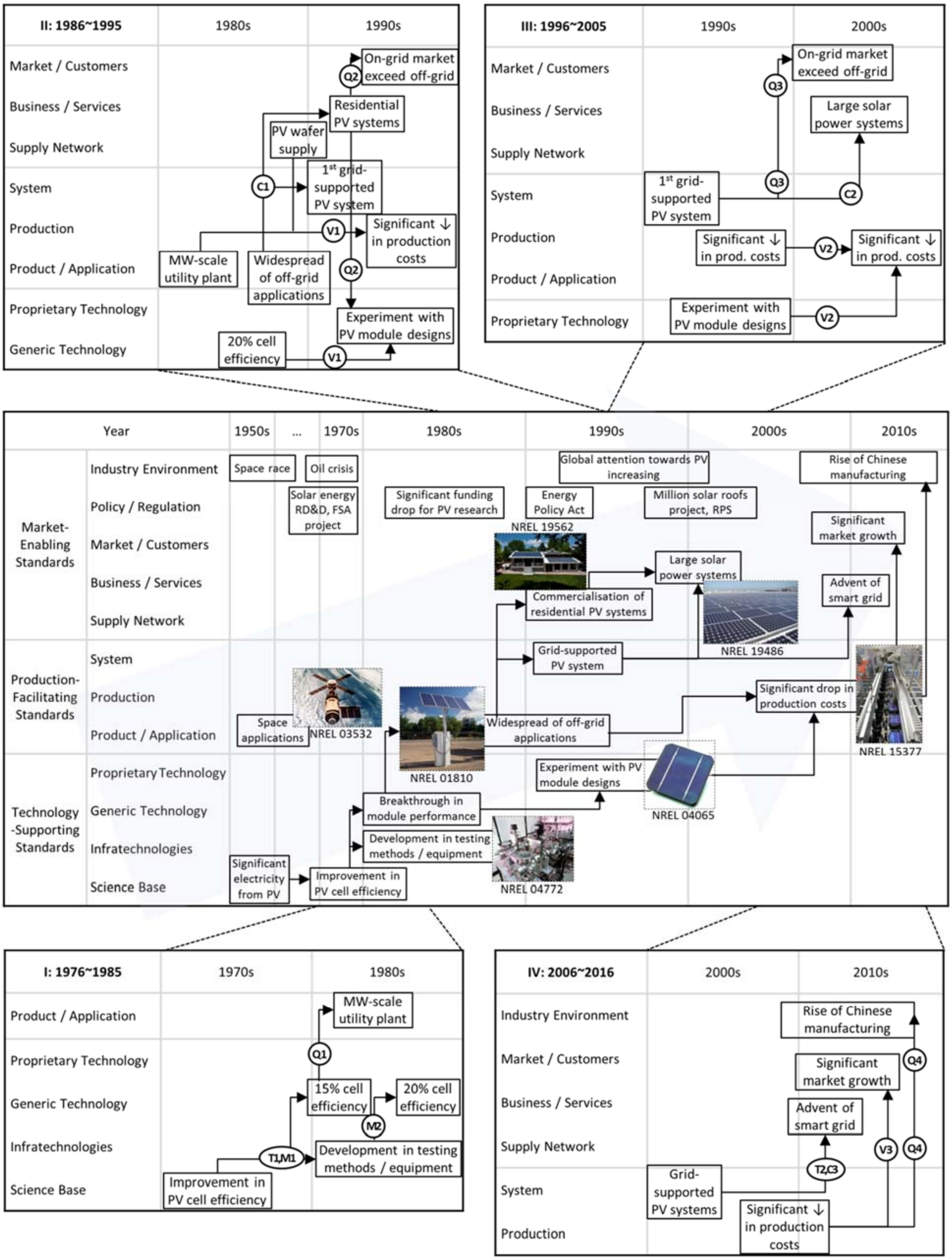

Fig.2 Analyses of standardisation during the innovation journey of PV technology (all images from NREL Image Gallery (NREL 2016)) (see Table 3 for details of standards codes)

Table 3. Dimensions of key standardisation activities highlighted in the case study

Phase	Code	Standard	What	Why	When	How	Where	Who
I	**T1, M1**	NASA TM 73702	Science base, Infratechnology, Generic technology	Terminology, Measurement/ characterisation	1977, Anticipatory/ Participatory	Technical report/Workshop agreement, Solution-describing, Government-based	Public agency	Early PV researchers
	Q1	JPL Block V	Generic technology, Product/applications	Quality/ reliability, Measurement/char'n	1981, Participatory	Performance/Solution-describing, Government-based	National laboratory	Early PV researchers
	M2	ASTM E891, E892, E948…	Infratechnology, Generic technology	Measurement/ characterisation	1982 ~ 1990, Participatory	Solution-describing, Committee-based	SSO	Mainly researchers from national labs
II	**C1**	IEEE 929	Product/applications, System, Business/service	Compatibility/interface	1988, Anticipatory	National standard, Solution-describing, Committee-based	SSO	System integrators / utilities / researchers
	V1	125mm wafer	Generic technology, Proprietary tech., Product/ applications, Production, Supply network	Variety-reduction	Early 1990s, Responsive	Performance-based, Market-based	Private companies	Manufacturers
	Q2	IEC 61215	Proprietary tech., Product/ applications, Business/ service, Market/customer	Quality/reliability, Measurement/ characterisation	1993, Participatory	International standard, Performance/Solution-describing, Committee-based	FSO	Researchers / manufacturers
III	**Q3**	UL 1741	System, Business/service, Market/customer	Quality/reliability, Compatibility/interface	1999, Anticipatory/ Participatory	National standard, Performance/Solution-describing, Committee-based	SSO	Researchers / installers / manufacturers
	C2	IEEE 1547	System, Business/service	Compatibility/interface	2003, Anticipatory/ Participatory	National standard, Solution-describing, Committee-based	SSO	System developers / utilities / researchers
	V2	Standard module design	Proprietary technology, Product/applications, Production	Variety-reduction	Early 2000s, Participatory/ Responsive	Performance-based, Market-based	Private companies	Manufacturers
IV	**V3**	SEMI standards	Production, Supply network, Market/customer	Variety-reduction Quality/reliability	2010s, Anticipatory/ Participatory	Performance/Solution-describing, Committee-based	Consortium	Equipment / material suppliers
	T2, C3	IEEE 2030	System, Supply network, Business/service	Terminology, Compatibility/interface	2011, Anticipatory/ Participatory	National standard, Solution-describing, Committee-based	SSO	Actors across all tiers of supply network
	Q4	IEC TS 62941	Production, Supply network, Market/customer	Quality/reliability	2016, Participatory	Technical specification, Performance/Solution-describing, Committee-based	FSO	Researchers / manufacturers

T1: Terminology standard for PV technology

One of the most significant information incorporated in the report was the definition of key terminologies, including cells, modules, and efficiency (NASA 1977). According to multiple interviewees, they helped to avoid potential confusion and to enhance communications among the PV community, when writing standards or using them for further research.

M1: Measurement and 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 measuring cell performances (NASA 1977). According to an interviewee, having a standard method of measurement made it easier to compare performances of cells developed by different groups, and also assess the current status of technology since research achievements could be traced more rigorously. Accurate assessments of research deliverables also helped program managers and government agencies in making funding decisions, so guiding research directions for further technology improvement.

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, noted interviewees. Hence, the US government initiated the Flat-Plate Solar Array (FSA) Project at Jet Propulsion Laboratory (JPL), requiring manufacturers to pass a set of prescribed tests in order to qualify for a series of PV module procurements (Colatat et al. 2009). Specifying both test procedures and performance criteria to pass the test, these specifications developed by JPL thus led to government-based standardisation for module quality. The standard resulted from *Block V*, the last 'block' of purchases in 1981, was particularly remarkable in helping designers and manufacturers develop high-quality products which, in turn, increased confidence among consumers (such as government and installation companies), according to multiple interviewees. It thus led to the widespread off-grid terrestrial applications; for example, the first large, megawatt-scale PV utility plant was built in 1983 (Yerkes 2004).

M2: Refined measurement and testing standards for PV modules

Due to increasing research activities in private sectors to meet the growing market demands, needs for more refined and publicly available standards were identified. Technical committees specifically dedicated to PV were thus established in various SSOs, including American Society for Testing and Materials (ASTM), Institute of Electrical and Electronics Engineers (IEEE), and Underwriters Laboratory (UL), so leading to committee-based standardisation. (Ross & Smokler 1986)

Based on their expertise in test methods and specifications, participants of ASTM E44 developed several measurement and testing standards in 1980s. Presenting spectral irradiance tables with more refined data and a strong technical basis, ASTM E891 and ASTM E892 enabled to produce verifiable and comparable results based on the same reference spectrum across the world, noted multiple interviewees. A series of standard methods for calibration and characterisation of reference cells (including ASTM E1039 and ASTM E1362) were also published, ensuring accuracy, stability, and reliability of efficiency results. 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).

According to interviewees, these solution-describing standards (i.e., outlining procedures without setting criteria) facilitated research activities of generic PV technology by providing a level playing field where everyone could be measured against. They also led to the development of measurement techniques and testing equipment, which were important infratechnologies themselves, thus allowing enhanced traceability and significant improvements in cell performances, despite the decreased public research funding in 1980s (Jones & Bouamane 2012).

5.2. Demonstration of grid-connected applications (1986~1995)

The significantly improved quality of PV modules, along with the increasing attention due to climate change in late 1980s, led to the growth of PV production and market. Yet, it 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 grids, noted interviewees.

C1: Compatibility and interface standard for residential PV systems

Compatibility and interface standards enabling the safe connection of PV systems with the utility were thus needed, in order to give confidence to utility companies, noted an interviewee. With their expertise in electrical systems, participants of IEEE SCC21 developed IEEE 929, which describes interface construction techniques and operating procedures for utility interface of residential and intermediate PV systems (Hester 2000). Prior to its development, PV applications had been treated as large-scale power generators, creating unnecessary barriers to its integration in larger grid systems, according to interviewees; this anticipatory standard thus allowed the commercialisation of on-grid, residential PV systems in early 1990s.

V1: Variety-reduction standard for wafer size

The demonstration of the potential for grid-connected systems in late 1980s led to the establishment of the PV market of significant size; and manufacturers started experimenting with the size of wafers specifically for PV modules, instead of those designed for computer chip manufacturing available at the time (Räuber 2003). By early 1990s, 125mm wafer (originally developed by Siemens and Sharp) was widely adopted as dominant design by wafer suppliers and module manufacturers, as it was found to generate high outputs with low production costs. According to multiple interviewees, this responsive, market-based standardisation based on a proprietary design led to the significant drop in production costs by generating economies of scale, and 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, International Electrotechnical Commission (IEC) published IEC 61215, the international standard for the design qualification of PV modules, in 1993 (Arndt & Puto 2010). As a participatory standard (subject to evolution, with improvements incorporated as experience is accumulated (Treble 1986)), this quality standard led to gradual improvement of PV products and systems (as manufacturers experimented to identify low-cost designs that could still pass the tests) and their wider deployment (Ossenbrink et al. 2012). It also facilitated product development processes, as new entrants could use them to identify and solve problems before market introduction (McConnell 2006). Multiple interviewees noted that as the PV industry grew and more manufacturers entered into the market, companies became more involved in standardisation, seeking competitive advantages by incorporating their proprietary technologies within quality standards.

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

With the increasing global awareness of and interest in renewable energy, US governments introduced a number of policy initiatives (e.g., 'Million Solar Roofs' and 'Renewable Portfolio Standard') to increase the PV market in late 1990s (Colatat et al. 2009; Räuber 2003). 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.

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

First, the quality of other electronic components required – such as inverters, batteries, and power controllers, all of which are called BOS – had to be ensured for users' (such as investors, installers, and project developers) confidence of PV systems. UL 1741, quality and safety standard for inverters, converters, and controllers, was thus developed in 1999 (Zgonena 2011). By increasing reliability and consumer confidence for larger PV systems, this national standard resulted in the wide adoption of on-grid PV applications and systems across the US, as claimed by interviewees and supported by data (Mints 2013).

C2: Compatibility and interface standard for PV power systems

The widespread use of various distributed energy resources (such as PV and wind) led to the identification of needs for compatibility standards to establish linkages between those with electric power systems (Basso 2009). IEEE 1547 was thus developed, in 2003, by a technical committee largely composed of representatives 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 for advanced communications among various products and systems, which was important for utilities 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, a number of dominant module designs with standardised dimensions (such as the number of cells per array, distances between cells, and location of junction boxes) appeared in early 2000s, according to an interviewee from the industry. He noted that this market-based standardisation, emerged in retrospective to module development, resulted in more economic production for manufacturers, by allowing the use of standardised equipment for production of PV modules.

5.4. Emergence of smart grid (2006~2016)

Due to the massive growth of PV production and market, relevant standardisation activities were conducted in various committees of multiple SDOs across the industry. The advent of smart grid (i.e., advanced power grid integrating varieties of ICT with existing power-delivery infrastructure) also required various standards to be developed by a diverse group of relevant stakeholders.

V3: Variety-reduction standards for mass production

First, there were urgent needs for standards related to production processes, in order to improve communications between manufacturers and suppliers, and achieve economies of scale through reduced variability in manufacturing processes, noted multiple interviewees. As many of the equipment and materials manufacturers in PV also had businesses in the semiconductor industry, existing standards published by Semiconductor Equipment and Materials International (SEMI) were modified when appropriate; in other cases, this consortium of supplier networks also developed new criteria, guidelines, and methods for PV-related process equipment, materials, or components (SEMI 2015). According to an interviewees, they resulted in lower production costs, as well as increased efficiency and consistency for process control, by improving traceability and optimising value-adding processes. 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 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 energy generators (including PV) with the grid, IEEE 2030 was developed in 2011, supporting information exchanges across their interfaces (Basso 2014). As the first standard in the emerging area of smart grid, it also included definitions of key terminology and language, facilitating communications among various stakeholders across all tiers of the supply network, according to an interviewee. He also noted that additional interface standards are to be developed in the future, to achieve successful interconnection of PV technologies with various other smart grid technologies and sub-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 did not guarantee the consistency of high quality products. IEC TS 62941 was thus published in 2016, specifying quality management systems required for PV manufacturers; it is expected to allow further production growth and cost reductions, by increasing consumer confidence in mass manufacturing (Wohlgemuth 2014). An interviewee noted that the development of a TS rather than an IS offers greater flexibility, allowing the industry to gather more data and information before ultimately developing more definitive IS.

6. Discussion

The longitudinal case study of PV demonstrates how the roadmap-based framework allows comprehensive analyses of evolving standardisation dynamics across multiple technology lifecycles. It does so by capturing all key dimensions of standardisation that are interdependent to each other in a holistic and integrative manner, overcoming limitations of existing frameworks with narrow perspectives. The framework can thus be used as both an analytical platform for long-term and system-wide analyses of standardisation in complex technological systems, and a practical foresight tool for developing coherent standardisation strategies to support innovation.

6.1. Integrative framework for systematic analyses of standardisation

The case study demonstrates needs for multi-cycle and multi-dimensional analyses of standardisation, by illustrating the relevance of all dimensions incorporated in the proposed framework. Drawing together key strategic issues addressed in existing conceptual models and important tactical issues highlighted in other literature, these dimensions help disaggregate complexity and variety associated with evolving dynamics of standardisation over multiple technology lifecycles with growing levels of systems complexity. Investigating them from holistic and integrative perspectives, the framework thus allows systematic analyses of how standardisation actually supports broad innovation systems.

6.1.1. Multi-cycle analyses of standardisation

Focusing on certain standardisation issues and contexts of technological innovation, existing frameworks discussed in section 2.1 are limited to observe only partial pictures of these dynamics from narrow perspectives. For example, while Tassey's (2000) framework can illustrate how various PV-related standards codifying different types of knowledge support diverse technological and innovation activities (see Fig.3), it does not account for their dynamic nature, so failing to capture how they evolve as PV technology develops and industry matures over time. Sherif's (2001) framework partly addresses this issue, relating different types of standards to different phases of technology lifecycles; however, it appears to be valid only within a single lifecycle of technology at a particular level of systems complexity (see Fig.4). Although it introduces the notion of transitions to a new substituting technology at the same level of systems complexity, it does not represent subsequent lifecycles with growing levels of (application) systems complexity, as repeatedly emerged throughout the PV history (further discussed below). In addition, Sherif's (2001) other frameworks (i.e., layered architecture of standards and a framework relating them to relevant SDOs) are appropriate for interface standards only in cases of ICT, neglecting other types of standards in general innovation contexts. Last but not least, Blind & Gauch's (2009) framework illustrates various functions of standards across different stages of research and innovation processes (see Fig.5 where multiple feedback loops are omitted for simplification), but is limited to address complexity and variety involved in technological systems. For example, it neglects multiple innovation paths for different application systems (e.g., off-grid standalone applications and large scale power systems) based on the same generic PV technology.

Existing conceptual models, therefore, provide neither a complete nor consistent picture of how standardisation supports broad innovation systems undergoing multiple technology lifecycles with varying levels of (application) systems complexity. Consequently, they do not offer sufficient guidance for relevant actors with long-term, multi-cycle, and system-wide perspectives to develop effective standardisation strategies in support of complex technological innovation systems. In addition, they not only lack empirical justifications, but also neglect tactical issues highlighted as important in practitioner studies and confirmed in the case study.

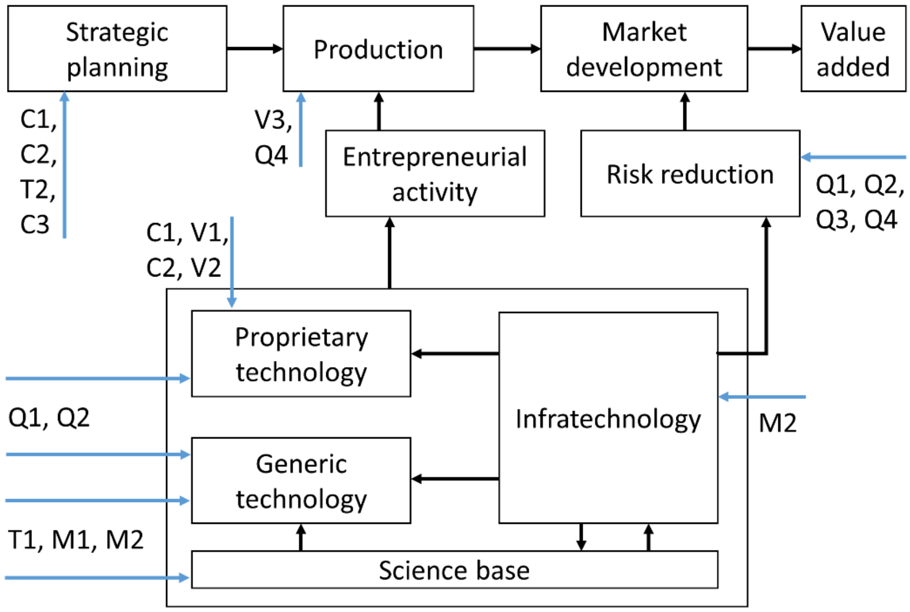

Fig.3 PV case study analyses using the framework by Tassey (2000)

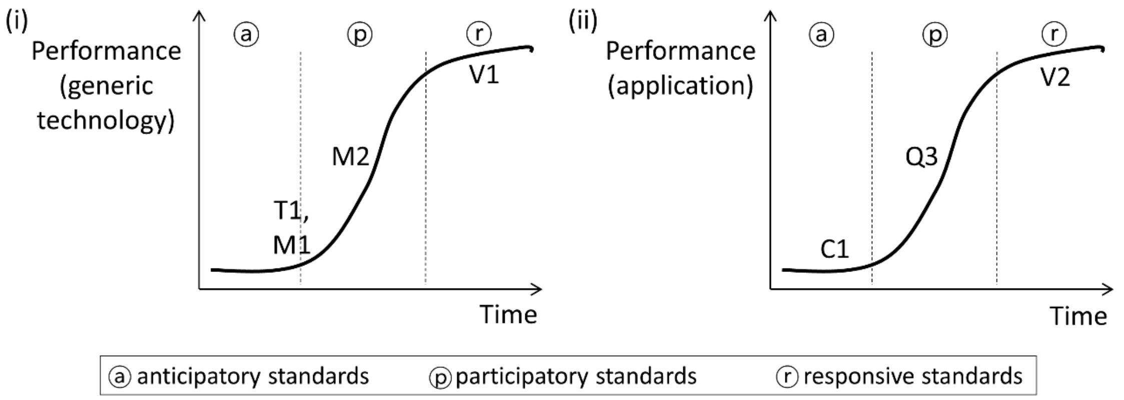

Fig.4 PV case study analyses using the framework by Sherif (2001)

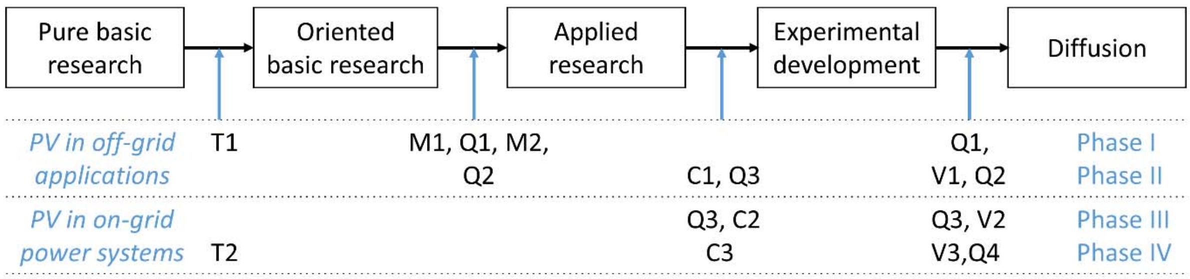

Fig.5 PV case study analyses using the framework by Blind & Gauch (2009)

Overcoming these limitations, the standardisation mapping framework systematically draws together different conceptual models, so providing more coherent, consistent, and integrative perspectives of standardisation in broad innovation systems. For example, while the Sherif's (2001) model is limited to only single lifecycle of technology at a particular level of systems complexity, the roadmap-based framework allows long-term and multi-cycle analyses of standardisation throughout the history of PV technology. Several technological and industrial dynamics have been observed, each focusing on different types of technology (or derived application systems using the technology) at different levels of systems complexity (i.e., generic technology of PV effects, proprietary technology of PV modules, standalone PV applications, and large grid systems). As suggested by Routley et al. (2013), multiple lifecycles thus emerged with different parameters (units of analysis) in the ordinate axis, 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 costs) (see Fig.6). Within each lifecycle, the timing of standards was closely related to the corresponding functionality that standards are associated with, as suggested by Sherif (2001); anticipatory standards at early stage of lifecycles, followed by participatory standards along with technology development, and finally responsive standards. Similar trends were repeatedly observed across multiple (subsequent) lifecycles of PV technology as the level of systems complexity grew; this was not captured in the framework by Sherif (2001), which only highlighted substituting technology lifecycles at the same level of systems complexity.

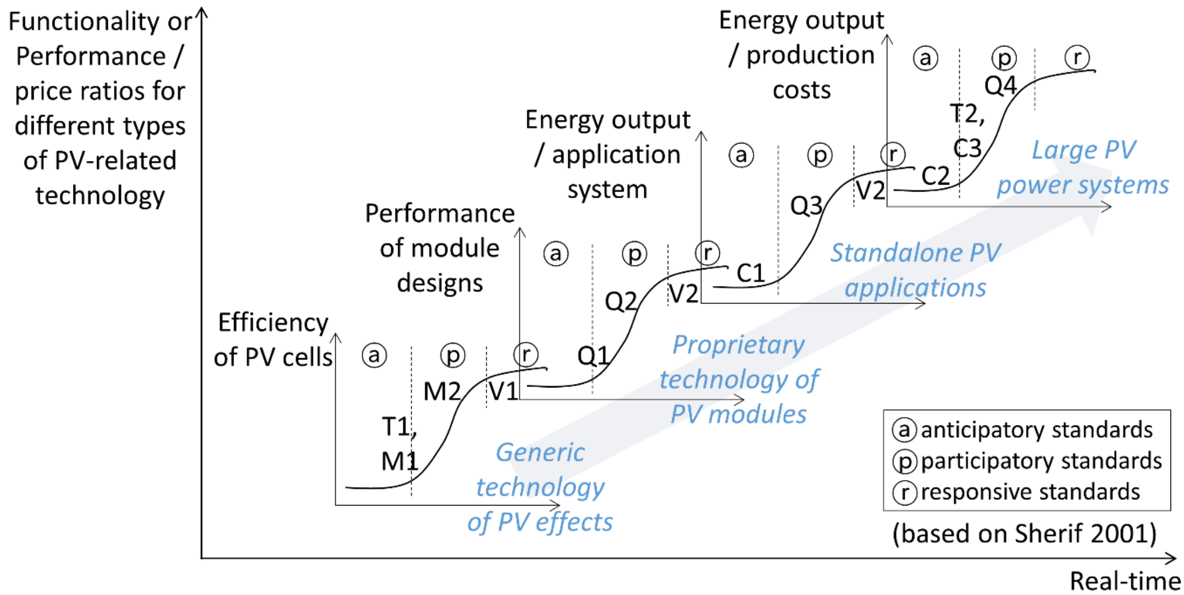

Fig.6 Timing of standards relating to multiple lifecycles of PV technology with growing levels of systems complexity

Thus allowing comprehensive, multi-cycle analyses of how all relevant dimensions of standardisation evolve over time, the proposed framework provides greater insights into standardisation across various stages of the innovation journey. For example, the emergence of responsive, market-based standardisation (e.g., standards wafer size and module designs) suggests the maturity of technology at a particular level of systems complexity, so implying the change of focus to applications systems at a higher level of complexity (as shown in Fig.6). Such insights into standardisation from multi-cycle perspectives could not have been produced by existing frameworks with particular focus only (e.g., Sherif 2001 highlighting committee-based standardisation only), which also resulted in the lack of longitudinal empirical evidence.

6.1.2. More comprehensive multi-dimensional analyses of standardisation

The standardisation mapping framework is shown to be more complete and comprehensive than the previous framework by Featherston et al. (2016), as it encompasses more refined dimensions of standardisation based on a systematic review of literature. It particularly incorporates tactical dimensions highlighted as important in practitioner studies and confirmed in the case study, as well as key strategic dimensions addressed in existing conceptual models. The importance and implications of these tactical dimensions were also highlighted by expert interviews of the in-depth case study, while previous studies were limited to documentary sources only.

For example, the tactical issue of '*how*' to standardise is found to be an important dimension, as certain types of deliverables may allow some levels of flexibility, providing room for further innovation in topics still under development. When standards are needed to increase broad customers' confidence, but are likely to change in the future, TS or PAS may be more effective in addressing such uncertainty, as processes of revising standards with low flexibility may take significantly longer. The case study also suggests different implications for different forms of specifications; while solution-describing standards (e.g., NASA technical report, ASTM standards) often spur incremental innovation of certain technologies or products, performance standards (e.g., JPL Block V, IEC 61215) tend to support their diffusion into markets by increasing user confidence.

The interrelated issues of '*where*' standards are developed and '*who*' is participating in standardisation are also important, as various types of stakeholders participate in different SDOs, depending on the mode of standardisation (i.e., another tactical issue of '*how*' to standardise). There are not only multiple actors associated with innovation activities of a particular type of technology (e.g., researchers from both private and public laboratories doing research on generic technology), but also many other types of stakeholders (e.g., users, government departments/agencies, and consultants), who are all involved in relevant standardisation. Furthermore, these participants continuously evolve over time across different phases of innovation. Such evolving diversities and details of stakeholder issues are neither appropriately captured in previous studies.

Therefore, the relevance of both strategic and tactical dimensions in disaggregating complex dynamics between standardisation and innovation is highlighted in the longitudinal, in-depth case study that provides robust empirical evidence drawing on both primary and secondary data. Reinforcing the need for a holistic and integrative approach for systematic analyses, the study also demonstrates that the standardisation mapping framework incorporates more complete and extensive list of relevant dimensions. Hence, it has the potential to be used as a more effective analytical platform for systematic analyses of standardisation, increasing our understanding of how it enables complex technological innovation.

6.2. Practical framework for strategic planning and management of standardisation

By extending the time axis to include the future, the proposed framework should also be effective for supporting strategic planning and management of standardisation efforts. This is becoming increasingly challenging due to high levels of complexity, interdisciplinarity, and systems-nature of modern technologies. As it is based on a generic roadmapping framework that is widely used for technology foresight and innovation planning (as discussed in section 2.2), it provides a structured platform for gathering collective intelligence to map future innovation activities and develop standardisation strategies. In particular, the new framework incorporates principles, structure, and insights that more fully account for key dimensions of standardisation over multiple technology lifecycles (with evolving levels of application systems complexity). This helps ensure that dynamics associated with key standardisation issues are considered in a coherent and integrative way, allowing more effective systematic anticipation of potential standardisation needs and consequences of relevant strategic decisions on innovation. As the framework needs to be adapted to the particular circumstances being investigated, the process of designing and configuring its dimensions and their detailed categories also provides learning experiences. By challenging practitioners to systematically consider diverse dimensions as they build the framework, it can offer further implicit guidance as to when and how different conceptual models may be relevant, so providing a basis for improved strategy development.

Such characteristics of roadmapping techniques suggests that roadmap-based frameworks, developed and tested through historical analyses, can be applied to inform future strategy in a variety of contexts, as argued by a number of studies (e.g., Phaal et al. 2011; Featherston et al. 2016). Multiple embedded cases across various phases of PV technology (focusing on different application systems), together with the generalisability of the generic roadmapping framework as well as existing standardisation frameworks integrated into it (i.e., frameworks by Tassey, Sherif, and Blind & Gauch), provide a degree of confidence that same structures and concepts are applicable to a broad range of technological fields. The framework is, therefore, expected to help decision-makers develop more coherent and effective standardisation strategies to enable innovation in various contexts of technological systems.

For example, the framework can help anticipate and prioritise technology areas where more efforts and resources are needed for standardisation and relevant R&D, in order to support complex innovation systems involving diverse technical domains at varying levels of systems complexity. By providing holistic and integrative perspectives to investigate various innovation activities and interactions between them, the roadmap-based framework provides a structured approach to identifying gaps in system linkages important for knowledge diffusion. It thus provides useful evidence bases for anticipating future standardisation needs to close such knowledge gaps, by helping identify what types of knowledge need to be codified (i.e., '*why*' standardisation is needed) to support certain innovation activities (i.e., '*what*' innovation activities are relevant to standardisation). This is particularly useful at transitions across different technology lifecycles, where long-term, multi-cycle, and system-wide perspectives are needed to ensure effective standardisation that supports the evolution of technology (application) systems to the next level of complexity (as suggested in Fig.6).

Once areas of future standardisation needs are identified, more practical decisions need to be made regarding various issues, including strategic issues addressed by some existing conceptual models (e.g., timing of standardisation), but also other tactical issues newly introduced in this study (e.g., modes of coordination, types of deliverables, and stakeholders involved in standardisation). Allowing systematic and integrative analyses of potential consequences of these dimensions, the proposed framework helps make more informed decisions in terms of '*when*' and '*how*' to standardise involving '*who*', for the timely and effective standardisation that enables innovation.

The consensus-based process of the roadmapping approach also makes the proposed framework a practically useful tool for strategic management and foresight of standardisation in complex technological innovation systems. Providing a communication platform where various stakeholders are brought together to make strategic decisions towards a common vision, the framework helps them achieve coherence and harmonisation of diverse standardisation activities, facilitating the overall innovation processes. These are particularly useful for standardisation of complex, interdisciplinary systems, which requires effective collaborations among experts from different backgrounds and disciplines (Ho & O'Sullivan 2017). The flexibility and scalability of the framework (as demonstrated from the longitudinal case study with four embedded cases focusing on various application systems) also provides a degree of confidence that it can be useful in supporting multidisciplinary collaboration, thus increasing potential values of the framework as a practical strategy tool.

7. Conclusion

This paper develops a novel standardisation mapping framework for systematic analyses of the interdependent dynamics of standardisation and technological innovation. The framework integrates, for the first time, key elements addressed in different conceptual models, which highlight only particular aspects of standardisation from relatively narrow perspectives. Thus providing a more complete and coherent picture than previous studies, the proposed framework allows us to develop systematic and comprehensive understanding of how standardisation supports innovation over multiple technology lifecycles. It is developed by integrating strategic dimensions (i.e., issues related to '*what*', '*why*', and '*when*') as well as tactical dimensions (i.e., issues related to '*how*', '*where*', and '*who*') within a holistic framework of roadmapping (building on the work of Featherston et al., 2016).

A longitudinal, in-depth case study of the emergence and evolution of PV technology highlights the importance of such holistic and integrative approach in understanding how standardisation supports innovation of complex technological systems. In particular, the framework has been applied to four embedded cases across multiple lifecycles of evolving PV applications, with growing levels of systems complexity. The study demonstrates the value of the framework's principles and structure for illustrating important dynamics between standardisation and technological innovation, especially during transitions between different lifecycles.

As the framework's integrating architecture is based on a widely-used foresight tool of roadmapping, it offers the potential to effectively deploy the framework for supporting strategic planning and management of standardisation. It can particularly help those innovation actors who need to take broader strategic perspectives (e.g., public agencies and SDOs) on the development of coherent, long-term, and system-wide strategies for standardisation in support of complex technological innovations. It does so by not only offering a novel and more comprehensive checklist of all relevant dimensions that need to be considered in a holistic way, but also providing insights and implicit guidance on their interdependence. Furthermore, the consensus-based nature of roadmapping means that the framework is intrinsically suited to supporting stakeholder collaboration for coherent and harmonised standardisation, which is increasingly challenging in complex, interdisciplinary technological systems.

While the PV case study highlights the merits of the integrated approach in analysing the interdependence of standardisation and technological innovation, there are additional opportunities for further research to advance our understanding of these dynamics. First, while multiple embedded cases in a single case study provide a certain level of generalisability, multiple historical case studies across a more diverse set of technological domains and different lifecycle transitions would help further explore and refine the framework's applicability in different contexts. Second, while the historical study demonstrates the value of the dimensions and principles of the framework, action-based research which applies the framework for future-oriented strategic analyses would help further test and refine the framework's potential as a foresight tool. Other areas of future research include: further analyses using more detailed categorisation of various types of stakeholders (e.g., according to factors such as their size and roles), exploring standards developed in diverse geographical areas (thus different institutional contexts), and various roles of government in standardisation.

In summary, the study makes significant contributions to the field of standardisation research by criticising, extending, and integrating existing conceptual models. In particular, the proposed framework overcomes limitations in our ability to analyse and understand the evolving role of standardisation in complex innovation systems with multiple technology lifecycles. It is also designed to support strategic planning and management of standardisation efforts, which are particularly challenging as modern technologies become ever more complex, interdisciplinary, and systems-like in nature.

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Appendix A. Dimensions of standardisation

Table A.1. Literature review on key innovation activities relevant to standardisation

Sub-groups	Innovation activities	Details	Exemplar references
Market-related activities	**Industry environment**	General activities of the industry outside the innovation system, providing contexts or backgrounds of other innovation activities	(Garcia et al. 2005)
	Policy / regulation	Political and legal issues, such as industrial policy, trade and competition, and regulations, that are closely related to standards	(Mansell 1995; de Vries 1999)
	Market / customers	Commercialisation and market development; standards reduce uncertainties and transaction costs in the market	(David 1987)
	Business / services	Firms' activities to provide business solutions / services, e.g., standards to gain market power through business models, often dominant designs	(Grindley 1995)
	Supply networks	Standards needed for efficient transactions within supply networks, involving materials, components, equipment, etc.	(Mansell 1995)
Production -related activities	**System**	Overall system of technologies integrating various components, e.g., standards for system designs of how different components and products are interconnected	(Tassey 2015)
	Production	Particular procedure or process executed for efficient production of product / application, e.g., standards for quality control or operational procedures	(Mansell 1995; OTA 1992)
	Product / application	Actual market applications formulated from generic technology to perform specific tasks / functions; product-related standards ensure that they are adequate for particular tasks, by specifying their characteristics	(OTA 1992; Tassey 2000)
Technology -related activities	**Proprietary technology**	Core value-adding technology where the concept from generic technology is formulated into a part of specific prototype products with specific performance / functions, conveying direct competitive advantages to companies	(Blind & Gauch 2009; Tassey 2000)
	Generic technology	Fundamental technical concepts derived from basic science for specific product innovations, and configured / reconfigured by industry to create proprietary technologies	(Tassey 2000)
	Infratechnology	Varied and critical technical infrastructure derived from other products or systems, supporting the development of generic technology, e.g., applied or industrial metrology such as measurement / test methods, interface standards	(Tassey 2000)
	Science base	Basic scientific principles representing fundamental laws – either method, procedural, or normative – or basic metrology, e.g., base units of measurement, such as mass, length and time	(Krechmer 1996; Tassey 2000)

Table A.2. Literature review on roles and functions of standardisation

Types of standards (depending on roles)	Details	Exemplar references
Terminology and semantic standards	Define common language and definitions to facilitate efficient communication among various stakeholders, e.g., unit and reference standards defining physical properties, classification and labelling schemes providing structured descriptions of entities	(Blind & Gauch 2009; David 1987; Krechmer 1996)
Measurement and characterisation standards	Specify methods for describing, quantifying, and evaluating comparable quantities, resulting in increased research efficiency, higher productivity and quality, e.g., publications, electronic databases, and test methods	(Blind 2004; Hatto 2013; Tassey 2000)
Quality and reliability standards	Specify acceptable criteria along various dimensions, such as functional levels, reliability, efficiency, health and safety, and environmental impact, in order to improve their performances, expanding market share through performance assurance and reduction in transaction costs	(Blind 2004; David 1987; Tassey 2000)
Compatibility and interface standards	Specify properties that a technology must have in order to be compatible (physically or functionally) with other products, processes, or systems, helping expand market opportunities by fostering network externalities, either directly (e.g., telephone network) or indirectly (e.g., hardware and software)	(Blind 2004; David 1987; Foray 1998)
Variety-reduction standards	Limit a certain range or number of characteristics, including both physical dimensions (e.g., size), and nonphysical, functional attributes (e.g., data formats), facilitating market formation and development by economies of scale and reducing suppliers' risks	(Hatto 2013; Swann 2010; Tassey 2000)

Table A.3. Literature review on timing of standardisation

Types of standards (depending on timing relative to technology lifecycle)	Details	Exemplar references
Anticipatory (prospective) standards	Developed shortly after the introduction of the new technology, specifying its production systems, such as definitions of new concepts, features, components, and tools needed to proceed with trial implementations. It is essential for widespread acceptance of a device or service.	(Sherif 2001)
Participatory (concurrent, or enabling) standards	Developed in parallel with market growth and performance improvement, for refinements in product systems. They not only reduce production costs, but also spur incremental innovation.	(Sherif 2001; de Vries 1999)
Responsive (retrospective) standards	Developed at the end of technology development, improving efficiencies or reducing market uncertainties by creating network externalities. There is also a danger that incompatible approaches may become well entrenched when standards emerge too late.	(Sherif 2001; de Vries 1999)

Table A.4. Literature review on types and forms of standard documents

Classification criteria	Types of standards	Details	Exemplar references
Types of deliverables	**International Standards (IS)**	Developed for topics with the highest level of maturity and a high degree of consensus	(Hatto 2013)
	Technical Specifications (TS)	Developed for topics that meet certain criteria, but are still under development or which have not reached a sufficient consensus, making specifications available for evaluation and accumulation of further knowledge and experience to be incorporated later	(Hatto 2013)
	Publicly Available Specifications (PAS)	Developed for subject matter that is at an even earlier stage of development but in urgent market needs for normative documents, encouraging to speed up standardisation in areas of rapidly evolving technology	(Hatto 2013)
	International Workshop Agreements (IWA)	Generated within the context of a workshop (even without any relevant technical committees), as fast deliverables for emerging areas	(Hatto 2013)
	Technical Reports (TR)	Prepared as informative documents without any requirements, simply providing background to a technical area or assisting with the application or interpretation of a full standard	(Hatto 2013)
Forms of specifications	**Performance (outcome-based) standards**	Specify desired outcomes or performance levels, allowing flexibility in product design while still meeting performance requirements, e.g., minimum standards of quality and safety may be specified to promote greater consumer protection	(Allen & Sriram 2000; Tassey 2000)
	Solution-describing (process-oriented, prescriptive-, or designed-based) standards	Provide detailed descriptions or precise specifications for exactly how designs or solutions could achieve these outcomes in a consistent and repeatable way, hence more restrictive	(Allen & Sriram 2000; Foray 1998; de Vries 1999)
Modes of coordination	**Committee-based standardisation**	Coordination through cooperation between stakeholders participating in committees of SDOs, consortia, professional associations, or trade associations.	(Wiegmann et al. 2017)
	Market-based standardisation	Coordination through competition between solutions (developed by any market player) in the market, leading often (but not always) to one de-facto standard.	(Wiegmann et al. 2017)
	Government-based standardisation	Solutions intended as a standard can come from various sources, but coordination through governments using their hierarchical position to impose these standards' use on others	(Wiegmann et al. 2017)

Table A.5. Literature review on organisations leading standardisation

Modes of standardisation	Types of organisations	Details	Exemplar references
Committee-based standardisation	**Formal Standards Organisations (FSOs)**	Can be national FSOs (e.g., BSI, DIN and AFNOR), regional FSOs (e.g., CEN, CENELEC and ETSI), or international FSOs (e.g., ISO, IEC and ITU), formally recognised by an authority and operating through governmental representations	(Hatto 2013; de Vries 1999)
	Sectoral or Specialised Standards Organisations (SSOs)	Professional or specialist organisations in particular business sectors or professional disciplines, including non-profit, industry-driven SDOs (e.g., ASTM) and professional engineering or scientific associations (e.g., IEEE)	(OTA 1992; de Vries 1999)
	Industrial Consortia / Research Initiatives	Emerging forms of SDOs in response to demands for the faster development of standards, formed by like-minded interests on well-defined projects or emerging areas of research (e.g., W3C, OASIS, IETF, and BioBricks)	(Blind & Gauch 2008; Sherif 2001)
Market-based standardisation	**Private companies**	Develop industry or proprietary standards for internal uses (within companies or their supply chains), that are widely accepted in the market, either voluntarily or through competition	(Allen & Sriram 2000; Branscomb & Kahin 1995)
Government-based standardisation	**Governmental bodies**	Can either impose mandatory use of standards developed elsewhere, or develop standards themselves and make their use mandatory	(Wiegmann et al. 2017)

Table A.6. Literature review on stakeholders participating in standardisation

Types of stakeholders	Details	Exemplar references
Consumers	End-users of products / systems paying special attentions to their quality, safety, certification, and conformity assessment to benefit from high-quality and low-price products, as well as their interoperability	(Garcia et al. 2005; de Vries 1999)
Government	Public sector bodies playing various roles – as convenor / coordinator, funder, rule maker, developer / advisor, participant, regulator / adopter, consumer, or interested observer – in standardisation for various reasons	(Garcia et al. 2005; Sherif & Seo 2013)
Industry (companies)	Producers (i.e., companies that use standards to get market success for their products), users (i.e., companies that buy products affected by standards, or use standards to incorporate into their production processes or systems), and various other entities (e.g., suppliers) across the value-chain	(Jakobs 2005; de Vries 1999)
Consultants	Professionals providing a leading edge in technology know-how, including consultancy firms as well as independent consultants	(de Vries 1999)
Researchers	Scientists and engineers from research laboratories (from both public and private), as well as academic researchers, not only providing sound technical base for standardisation, but also benefiting from more accurate measurement and instruments	(Blind & Gauch 2009; Garcia et al. 2005)
Others	Other entities such as trade unions, non-governmental organisations, and training entities	(ISO TC 207 2006; de Vries 1999)

Appendix B. Interviews in the PV case study

Table B.1. 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	British Standards Institution (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	Solar Energy Industry Association (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	Department of Energy	Participation from government agency	IEC	2 interviews
30	North American Board of Certified Energy Practitioners (NABCEP)	Participation from industry		Via phone

31	National Institute of Standards and Technology (NIST)	Participation as researcher from laboratory	IEC	
32	University of Delaware	Participation as researcher from academia	IEC	Via e-mail
33	National Rural Electric Cooperative Association (NRECA)	Participation from industry	IEEE	
34	NREL	Participation as researcher from laboratory	ASTM	
35	National Institute of Standards and Technology (NIST)	Participation as researcher from laboratory	ASTM	
36	Department of Energy	Support for standardisation activities from government agency		
37	Department of Energy	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	National Aeronautics & Space Administration (NASA) (past)	Participation as researcher from laboratory		
42	TetraSun	Participation from industry	IEC	