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Addressing the evolving standardisation challenges of ‘smart systems’ innovation: Emerging roles for government?

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Abstract

At a time when standardisation is increasingly recognised as an important area of innovation policy, the emergence of cyber-physical ‘smart systems’ presents significant challenges. Such complex technological systems have unprecedented levels of complexity and interoperability requirements, and pervade many critical national infrastructures, so calling for active roles for government to support their effective standardisation. Existing literature, however, offer limited insights into where, why, and how policy intervention can address the evolving variety of innovation challenges associated with standardisation. This article, thus, proposes a novel innovation systems-based framework, for structured analyses of complex dynamics between standard-related innovation problems, relevant roles of government, and appropriate policy instruments. The historical case study of photovoltaic technology (from its early R&D to integration into Smart Grid) illustrates the framework, and provides practical implications for policymakers, suggesting evolving roles of government in the transition to cyber-physical smart systems in response to growing risks of systemic problems.

Key words: standard; innovation policy; innovation system; smart system; photovoltaic technology; Smart Grid.

1. Introduction

Effective standardisation is increasingly identified as an area of important innovation policy interest, following increased understanding of the critical roles that standards can play in supporting technological innovation (Borrás and Edquist 2013; Edler and Fagerberg 2017; Woolthuis et al. 2005). In addition to the traditional role of promoting industrial and commercial efficiency, standardisation is recognised as having the potential to support a variety of innovation activities through, for example, codifying accumulated technical ideas and best practice experiences, establishing common foundations upon which innovative technology may be developed, and allowing interoperability between various products and systems (Allen and Sriram 2000; Blind 2016; Hawkins 2017; Swann 2010). In this context, many governments across the world have recently started introducing a variety of policy initiatives to promote timely and effective standardisation in support of their national innovation systems (ANSI 2015; European Commission 2011).

Despite increasing policy efforts related to standardisation, government and public agencies face significant challenges in determining where, why, and how policy intervention is needed for effective standardisation. In particular, there is a lack of systematic evidence regarding the complexity and variety of standardisation-related innovation bottlenecks and potential roles of government to address them. This is, in part, because existing academic literature are still confined in traditional conceptualisations of standardisation, focusing on certain types of standards (e.g. product standards) that play conventional roles of promoting industrial and commercial efficiency. Not adequately exploiting recent advances in our knowledge of standardisation (i.e. its complex and dynamic nature, particularly in progressively complex technological innovation systems), such studies identify only limited scope for policy intervention in standardisation (Greenstein 1992; Grindley 1995). Although some recent innovation studies do acknowledge potentially greater policy needs in standardisation (Blind 2016; Tassey 2017), they identify ‘lack of appropriate standardisation’ as a single innovation bottleneck, providing policymakers with limited insights into the evolving variety of standard-related innovation challenges.

Such insufficient guidance provided by existing literature presents ever more increasing challenges, as the emergence of large-scale infrastructural systems incorporating a wide variety of Information and Communication Technologies (ICTs) has resulted in calls for greater policy needs to ensure their timely and effective standardisation (European Commission 2011; NIST 2011). The transition into such cyber-physical 'smart systems'[1] with the unprecedented level of complexity has proliferated the number and variety of standards needed to allow communication and interoperability between the large number of components and subsystems interconnected with each other (NIST 2011). These standards are also becoming more essential than ever for a nation's economic development, as well as security, environment, and quality of life, as modern economies and societies increasingly rely on such complex systems in diverse infrastructural areas, such as energy (e.g. Smart Grid), transportation (e.g. electromobility), and industrial production (e.g. Smart Manufacturing) (e.g. DKE 2014; NIST 2011; NPE 2012). Effective development and management of the sheer number and variety of standards are thus increasingly important, yet also challenging, as they require coordination among a multiplicity of innovation and industrial actors with different backgrounds as systems become more convergent and cross-sectoral (DKE 2014; NIST 2011). For example, standardisation of electromobility requires coordinating and integrating diverse activities in the domains of electrical engineering, ICT, and automotive technology, whose standardisation used to be viewed as separate activities (NPE 2012).

The growing public interest and practical challenges associated with technical standardisation, due to the emergence of complex smart systems, urge government to reconsider its roles in standardisation. However, existing literature—mostly published before the emergence of cyber-physical smart systems—are limited to justify increasing needs of, or provide informed guidance for, policy initiatives recently proposed in practice, as further discussed in Section 2. In order to fill this gap between theory and practice, this article proposes a novel framework for analysing the evolving roles of government in standardisation of complex technological systems by integrating relevant dimensions and elements of innovation systems-based frameworks. The proposed framework is illustrated using a historical case study of Photovoltaic (PV) technology (from its early R&D to recent integration into Smart Grid); rationales for the case selection and the methodology underpinning the case study are summarised in Section 3. Section 4 summarises details of the case study, demonstrating how the framework enables more structured and systematic analyses of where, why, and how policy intervention is needed to support effective standardisation. Section 5 then discusses how this study (and a review of recent studies) offers insights into potential roles for government in addressing innovation bottlenecks associated with standardisation of complex cyber-physical smart systems. The article concludes by reflecting on the practical implications to provide policymakers with more informed guidance in designing appropriate policy actions to promote effective standardisation in support of complex technological innovation systems.

2. Literature review

This section first presents an up-to-date review of existing literature on policy intervention in standardisation, most of which are increasingly limited in explicating the growing policy needs in standardisation, in the era of ever more complex technological systems. Because these studies, largely based on neoclassical economic theory, fail to distinguish the evolving variety of innovation bottlenecks associated with standardisation of complex technological systems, the Systems of Innovation (SI) perspective is proposed as a more appropriate theoretical basis. In particular, useful dimensions and elements of SI-based frameworks are introduced to allow more structured analyses of where, why, and how policy intervention may be used to ensure timely and effective standardisation in support of complex technological innovation systems.

2.1 Existing literature on policy intervention in standardisation

Recognising the importance of standards in promoting industrial and commercial efficiency, existing economics literature adopting the predominant neoclassical approach has identified potential scopes for policy intervention to ensure effective standardisation (David and Greenstein 1990; Farrell and Saloner 1985). As standards can be viewed as a 'public good' with non-rival and non-exclusive characteristics (i.e. benefits are available to everyone and from which no one can be excluded), the market may not be sufficient to result in a socially optimal choice of standards (Berg 1989; Kindleberger 1983). In networked technologies with large installed bases, users may also get locked-in to an old standard due to significant 'excess inertia', suggesting needs for government intervention to manage coordination of decisions across different users (Farrell and Saloner 1985). Other market failures associated with standardisation include problems of market fragmentation, high costs of standards competition or duplication, stranding users with non-standard technology, and severe risks of monopoly (David and Greenstein 1990; Spruyt 2001; Swann 2010), all of which reduce benefits of standardisation in the overall economy.

Despite such problems with market solutions of standardisation, government involvement is often not recommended as exogenous forces (e.g. dramatic technical change) outstrip ability of any administrative processes, thus making market participants more effective decision-makers (Greenstein 1992). David (1987) highlights the problem of 'blind giants', that is, there are narrow windows for effective policy intervention, and public agencies are likely to be at their most powerful in exercising influence when they know least about what should be done. Other risks of government failures in standardisation include: difficulty in reaching agreement on the contents, form, and timing of standards; political losses due to vested interests; lobbying; and slow administrative processes (e.g. Greenstein 1992; Grindley 1995; Tassey 1982).

Hence, previous literature based on neoclassical economic theory generally suggest limited engagement of government in standardisation, except in certain areas of critical public interests (e.g. national security, health and safety, and environment), or areas where they hold authority to regulate the market (e.g. spectrum management in radio frequencies) (David and Greenstein 1990; Spruyt 2001). Indirect intervention through providing public funding is also recommended only in cases of strong 'public good' infratechnologies (e.g. tools needed to develop metrology and measurement standards), which are characterised by indivisibilities, large-scale research facilities, and long-time horizon for payback on investments (Greenstein 1992; Tassey 1982). Active roles of government are generally accepted when they are technically better informed than the market (thus reduced risks of government failures), but this mostly applies to certain developing countries with relatively weak technological capabilities of other market players (e.g. Gao et al. 2014; Wang and Kim 2007).

Although a few scholars suggest recently increasing roles for government to ensure effective standardisation in developed countries, only narrow scopes for policy intervention are discussed in a limited and unsystematic way. For example, Blind (2016) and Tassey

(2017) identify potential policy needs in broader scopes of standardisation (i.e. technical specifications and infrastructure for efficient research) but mostly limited to financial support for relevant infratechnologies and early R&D activities only. Swann's (2010) analyses are also limited to selected, existing policy areas; in addition, he adopts the system failures concept to 'complement' insufficient justifications of market failure rationales, even though they are based on theoretical perspectives whose underlying assumptions are fundamentally incompatible with each other (Chaminade and Edquist 2010; Dodgson et al. 2011).[2] While some recent studies in sociology and political science (e.g. Funk and Methe 2001; Meyer 2012) discuss coordinating and mediating roles for government to address potential risks of social conflicts among various stakeholders involved in international telecommunications systems, they suggest limited roles of policy for fear of exposing standardisation to political contestation.

2.2 Limitations of existing literature and the SI perspective to address them

The review of existing academic literature shows their limitations in justifying increasing needs of, or providing useful guidance for, policy intervention to ensure effective standardisation of complex smart systems. This is mainly because they do not adequately explore recent advances in our knowledge of standardisation (particularly in progressively complex innovation systems), neglecting variety and complex dynamics associated with it. There is, however, an increasing understanding that standardisation is a complex and dynamic process, as there are various types of standards (related to processes, tools, methods, systems, etc.) playing a variety of roles (e.g. diffusing innovative knowledge, establishing common platforms, and allowing interoperability in complex systems) at different stages of innovation journey (Allen and Sriram 2000; Blind 2016; Hawkins 2017; Swann 2010). Yet, existing policy-related studies on standardisation—largely focused on product standards intended for commercial efficiency—often consider standards as something static and inflexible, thus inhibiting innovation (e.g. Greenstein 1992; Grindley 1995). Mostly based on the market failure rationale of neoclassical economic theory, they are also confined in a traditional perspective that standards are developed from either purely market- or purely government-driven activities. This contrasts with a recent trend of hybrid standardisation processes involving public and private partnerships, suggesting diverse and informal roles of government in standardisation of complex smart systems (De Bruijne and Van Eeten 2007; Wiegmann et al. 2017).

Such limitations of existing literature in exploring the variety and complex dynamics associated with standardisation and potential roles of government can be overcome by adopting the SI perspective. Focusing on the dynamic complexity of systemic combinations of 'all important economic, social, political, organisational, institutional and other factors that influence the development, diffusion and use of innovation' (Edquist 1997: 14), it allows to systematically explore evolving complexity and diversity associated with standardisation. In addition, recent studies, highlighting increased systemic risks associated with large-scale networked systems (such as Smart Grid and Internet of Things), suggest that a systemic approach is required to increase our understanding of growing and diverse policy needs in standardisation of complex smart systems (De Bruijne and Van Eeten 2007; Orwat 2011). Despite its potential to provide more systematic and informed guidance for appropriate roles of government in standardisation, the SI perspective has been largely underexploited by existing studies. While many SI literature acknowledge the importance of standardisation and potential policy needs in cases of 'lack of appropriate standardisation', it is often identified as a single innovation bottleneck, without further analyses into various rationales for, and designs of, relevant policy intervention (e.g. Borrás and Edquist 2013; Edler and Fagerberg 2017).

In order to fill this research gap, this article adopts the SI perspective as a more adequate theoretical basis for detailed and systematic investigation of where, why, and how policy intervention may be used to promote timely and effective standardisation, so supporting overall innovation systems. It provides policymakers with more informed guidance for appropriate policy designs, by allowing them to navigate through complexity and variety of innovation bottlenecks associated with standardisation, so leading them to more effective policies to address existent problems in innovation systems under study. It can thus overcome limitations of neoclassical economic theory, which is often criticised to be an inadequate basis of policy action in increasingly complex and dynamic innovation (e.g. Chaminade and Edquist 2010), as it only 'focus[es] on a limited set of levers aimed at mimicking optimal market outcomes by making marginal adjustments' (Dodgson et al. 2011: 1146).

2.3 SI-based frameworks as more adequate bases of policy action

Building on recent understanding from SI literature that standardisation is an evolving and dynamic process, Ho and O'Sullivan (2018) developed a roadmap-based framework for systematic analyses of such complex dynamics in technological innovation systems. Extending and integrating existing concepts and models presented in key standardisation literature (including Tassey 2000, Sherif 2001, and Swann 2010), they developed an analytical framework characterising various dimensions of standardisation in a comprehensive and integrative way. It helps navigate through the diversity and complex dynamics associated with standards playing various roles and functions (e.g. measurement standards, quality standards, and interoperability standards), relevant to different types of technologies (e.g. infratechnology, generic technology, and application systems), and developed at different stages of innovation. The framework can thus be used to clearly identify any standard-related bottlenecks and gaps that make an innovation system not operating well.

Once the framework by Ho and O'Sullivan (2018) reveals various different types of innovation bottlenecks related to standardisation, a systemic policy framework developed by Wieczorek and Hekkert (2012) can be used for further analyses to identify causes of these systemic problems, so that appropriate policy instruments can be designed to effectively address them. Although some literature (e.g. Woolthuis et al. 2005) use the term 'systemic failure', it implies the notion of optimal status, which is inapplicable (as discussed in Section 2.2), thus the term 'systemic problem' is preferred (Chaminade and Edquist 2010). There are four types of systemic problems, each associated with each of four structural elements of innovation systems (i.e. actors, institutions, interactions, and infrastructure). Analysing presence (or absence) and capacities (or qualities) of these structural elements points to problematic elements that require potential policy intervention, so providing a basis of formulating appropriate policy objectives and recommending policy designs that are more suitable to address current systemic problems (Wieczorek and Hekkert 2012; Woolthuis et al. 2005).

Table 1. Structural elements and relevant systemic problems associated with standardisation

Structural elements	Examples	Relevant systemic problems	Examples of potential systemic problems associated with standardisation
Actors	• Companies: start-ups, large firms, multinationals. . . • Knowledge institutes: universities, technology institutes, research centres • Government • Non-government organisations • Other parties: legal / financial organisations, intermediaries, consultants. . .	• Absence of relevant actors • Actors' lack of competence or capacity: • to learn or utilise available resources • to identify and articulate their needs • to develop visions and strategies	• Actors' lack of capacity / resources (or interest) toinitiate standardisation, particularly in areas of high relevance for society (Blind 2016; Funk & Methe 2001) • Absence of SDOs (or existing SDOs' lack of capacity / resources) to engage diverse stakeholders and moderate their varying interests (Funk & Methe 2001; Gao et al. 2014) • Actors' lack of capacity / resources to participate in standardisation or conduct relevant R&D required (Blind 2016; Tassey 2000) • Standard users' lack of capacity / resources to access to relevant standards (Swann 2010)
Institutions	• Hard: rules, laws, regulations • Soft: customs, common habits, routines, established practices, traditions, norms, expectations	• Absence of specific institutions • Capacity/quality-related problems: • stringent institutional problems • weak institutional problems	• Absence of laws / regulations mandating particular standards critical for public purposes (e.g., public safety, defence) (Meyer 2012; Spruyt 2001) • Absence of clear policies relevant to standardisation (Garcia et al. 2005) • Lack of common standards, leading to market fragmentation, standards competition, stranding users, risks of monopoly (David & Greenstein 1990)
Interactions	• At level of networks • At level of individual contacts	• Absence of interactions due to distance between actors, different objectives, or lack of trust • Quality / intensity-related problems due to strong / weak network	• Absence of interactions between different actors due to conflicting interests (David & Greenstein 1990) • Strong network around old / inferior standards leading to excess inertia (Farrell & Saloner 1985; Swann 2010) • Strong network wrongly guiding collective actions (Meyer 2012)
Infrastructure	• Physical: artefacts, instruments, roads, building, networks • Knowledge: expertise, know-how, strategic information • Financial: subsidies, financial programs, grants	• Absence of specific type of infrastructure • Inadequate or malfunctioning of specific type of infrastructure	• Absence of physical infrastructure (i.e., testing facilities / technical instruments) required for large-scale R&D relevant to standardisation (Tassey 1982, 2000, 2017) • Lack of knowledge / information about standards, particularly their updates (Farrell & Saloner 1985; Swann 2010)

Source: Authors' analyses of potential systemic problems identified from the standardisation framework by Ho & O'Sullivan (2018), using the concepts of structural elements as defined by Wieczorek & Hekkert (2012)

Table 1summarises how dimensions and elements of these two SI-based frameworks can be integrated to provide a complete and detailed 'checklist' of why systemic problems may possibly occur in association with standardisation, by allowing systematic diagnoses of standard-related problems in innovation systems under study. The first two columns of Table 1 list various examples of structural elements of innovation systems and systemic problems associated with them, as identified by Wieczorek and Hekkert (2012). Applying these concepts of structural elements to innovation bottlenecks identified by Ho and O'Sullivan's (2018) framework allows systematic analyses of potential problems (and their causes) associated with standardisation; examples of these systemic problems, as identified in existing standardisation literature, are summarised in the last column of Table 1. Thus, allowing more detailed structural analyses of diverse systemic problems than previous literature that simply consider them as a single innovation bottleneck, these frameworks help navigate through the variety and complex dynamics associated with standardisation, particularly in increasingly complex smart systems.

The problem-oriented approach of the systemic policy framework can also guide governmental authorities to formulate appropriate policy objectives and goals, which in turn suggest effective policy actions to achieve these goals (Edler and Fagerberg 2017; Wieczorek and Hekkert 2012). The wide diversity of systemic problems associated with standardisation requires diverse public agencies to adopt various policy instruments (as identified in Blind 2016; NIST 2011), in order to effectively address the problems by precisely targeting to alter particular elements causing them. Existing literature report a number of different policy instruments that can be used in practice; categorised according to the general threefold typology suggested by Borrás and Edquist (2013), these are summarised in Table 2.

Firstly, regulatory instruments use legal tools (e.g. laws, rules, and directives) for the regulation of social and market interactions, so that innovation actors are obliged to act in accordance with what is ordered in these rules and directives. Secondly, economic and financial instruments provide specific pecuniary incentives (or disincentives), in order to support particular activities of innovation

Table 2. Examples of policy instruments used relevant to standardisation

Types	Examples of policy instruments	References
Regulatory instruments	• Establishing legal foundations for standardisation systems	(Spruyt 2001)
	• Implementing and mandating particular standards by citing in legislations / regulations	(Funk & Methe 2001; Meyer 2012)
Economic and financial instruments	• Enabling standardisation activities by providing financial supports / benefits to SDOs / participants	(Gao et al. 2014; Swann 2010)
	• Providing financial supports to research institutes to develop standards through its own R&D	(Blind 2016; Tassey 1982)
	• Providing financial supports to access to certain standards	(Swann 2010)
	• Using purchasing power in public procurement to promote certain standards	(Blind 2016)
Soft instruments	• Engaging / moderating diverse stakeholders with varying interests in standardisation activities	(Gao et al. 2014; Garcia et al. 2005; Spruyt 2001)
	• Providing information on particular standards to promote their use	(Farrell & Saloner 1985)
	• Maintaining standards databases	(Swann 2010)

Source: Authors' analyses of various policy instruments discussed in existing standardisation literature (refer to references), using the typology of policy instruments suggested by Borrás & Edquist (2013)

actors without obligating them. Lastly, characterised by being voluntary and non-coercive, soft instruments largely complement regulatory and economic instruments to influence innovation actors through less hierarchical forms, such as transfer of knowledge or persuasion. In order to be able to choose appropriate instruments among them, it is necessary to know main causes of innovation problems; the IS-based policy framework provides an analytical basis of exploring them by allowing systematic and problem-oriented analyses, rather than directing to specific policy designs to be effective (Borrás and Edquist 2013).

3. Research methods

3.1 Case study of PV technology in the USA

For systematic investigation of where, why, and how policy intervention is needed to promote effective standardisation in support of innovation, this article conducts an in-depth case study using the analytical frameworks presented in Section 2.3. In particular, a historical case study is carried out, in order to highlight the evolution of standardisation landscapes due to the recent transition to complex smart systems, so helping us explicate the increasing and diverse policy needs in standardisation. Such 'history-friendly' research by studying the diversity of rationales, designs, and experiences of policy actions also provide good sources for policy making and policy learning, as the complex evolutionary perspective of innovation systems does not self-evidently provide definitive and highly-specified policy recommendations (Borrás and Edquist 2013; Dodgson et al. 2011). Nevertheless, due caution needs to be taken in drawing lessons for other contexts, as policy instruments are very context-dependent, and there are no 'one-size-fits-all' solutions; hence, they need to be designed with specific problems in particular innovation systems in mind (Borrás and Edquist 2013).

Given high levels of variety and complex dynamics associated with standardisation in innovation systems (as discussed in Section 2.2), as well as the cumbersome nature of historical in-depth studies, a single case study has been conducted for practical reasons. The case of PV technology (from its early R&D to its recent integration into Smart Grid) is selected because of its long history, as well as technical complexities and variations involved, all of which provide rich information relevant to standardisation. Diverse stakeholders and Standards Developing Organisations (SDOs) have been involved to develop various standards relevant to different types of PV technologies (e.g. PV cells and modules, standalone off-grid systems, and on-grid systems connected to utilities) and its application systems (from space and telecommunication sectors to residential and utility applications) over time (see Ho and O'Sullivan 2018 for detailed historical accounts of the innovation and standardisation of PV technology). Due to such complexity and variety, we can explore various different types of systemic problems that have appeared in association with standardisation, and a range of different policy actions introduced by diverse policy actors to address these innovation bottlenecks. In particular, the integration of PV technology into Smart Grid (a typical cyber-physical smart system that is critical in modern society) allows us to investigate growing needs for, and various roles of, policy as standardisation landscapes evolve in response to the recent transition to complex smart systems.

This study particularly explores how various government and other public agencies in the USA have engaged in the standardisation of PV technology. This is mainly because the USA is the birthplace of both PV technology and Smart Grid, where many of early innovation and standardisation activities took place; SDOs based in the USA thus dominated their early standardisation, thereby having significant influences in international standardisation later. The case study of the USA also demonstrates the importance of policy intervention in standardisation, even in countries with liberal market economies where many standard settings are driven by the market (as opposed by publicly-funded SDOs in some countries) (Tate 2001).

3.2 Data collection and analyses

Given its retrospective nature, this study employed historical event analyses combined with interviews, as adopted by recent SI literature focusing on policy issues (Negro et al. 2007; Reichardt et al. 2016). Over 200 documents from various sources and perspectives (including professional journals, standard publications, industry trade magazines, websites, and official reports published by government) have been reviewed to retrieve as many historical events and activities related to standardisation and relevant policy intervention. Stored in a database in a chronological order, these events constitute the evidence base for our systematic analyses of where, why, and how policy has intervened to support effective standardisation.

In order to complement and triangulate the data collected from documental sources, we also conducted semi-structured interviews with experts who have been involved in various standardisation activities. Providing contextual backgrounds and details that might be difficult to access through documentation alone, interview transcriptions provided not only rich data for the database but also insights into interdependences between various systemic problems and policy intervention. After seven preliminary interviews with experts involved in standardisation of PV and Smart Grid, a broader group of interviewees were initially contacted from the list of members in technical committees for PV in major SDOs (ASTM E44, IEC TC82, and IEEE SCC21) and then approached using 'snowball sampling' (Goodman 1961). A total of forty-eight experts from various stakeholder groups and diverse disciplinary perspectives participated in interviews, providing balanced and varied perspectives on standardisation and relevant policy intervention throughout the history of PV and Smart Grid. Appendix Table A.1 presents details of their profiles, yet maintaining the interviewees' and their organisations' anonymity.

The collected data were then analysed using dimensions and elements of the frameworks presented in Section 2.3 (Ho and O'Sullivan 2018; Wieczorek and Hekkert 2012). They help us zoom in on potential areas of systemic problems associated with standardisation, roles of government to address them, and appropriate policy instruments to support overall innovation systems.

4. Policy intervention in standardisation of PV and Smart Grid in the USA

This section presents historical analyses of policies adopted in the USA to promote timely and effective standardisation of PV technology, from its early R&D to its recent integration into Smart Grid. Using the frameworks based on SI perspective to analyse where, why, and how policy has intervened, it provides a rich description of which systemic problems existed in association with standardisation and what policy instruments have been introduced to address them (it is, however, to be noted that this article does not discuss every policy intervention throughout the history but rather selected examples illustrating a variety of policy instruments to address diverse systemic problems). The period of over 40 years is divided into three broad phases according to the evolution of main application systems being standardised (i.e. PV cells and modules, PV applications and systems, and Smart Grid systems). Structured around significant standardisation activities that played critical roles in supporting innovation and development of PV and Smart Grid, these historical accounts are also summarised in Table 3 at the end of each phase.

4.1 Phase 1: early standardisation of PV cells and modules (1974–1990)

4.1.1 ERDA/NASA terrestrial PV measurement workshop

Since the oil crisis in the 1970s, PV gained great attention as an alternative source of energy, leading to a growing number of organisations involved in research on solar cells for terrestrial applications (Ho and O'Sullivan 2018). Although needs for common standards to increase their research efficiency were identified, there were neither relevant SDOs nor private actors willing to drive standardisation activities in this emerging technology with high costs and risks, according to interviewees. Government agencies with more experiences (from research on space applications) and available resources thus took the leadership to gather the industry on board; the Energy Research and Development Administration (ERDA) funded and organised two joint workshops with the National Aeronautics and Space Administration (NASA), which resulted in the technical report (NASA TM 73702) presenting the first set of government-based standards in PV technology (NASA 1977). Given the capital-intensive, large-scale infrastructure and specialised knowledge required for standardisation related to science base, participants of these workshops were mainly staff from public agencies (e.g. ERDA and National Bureau of Standards) and researchers from national laboratories (e.g. NASA Lewis Research Center, Sandia Laboratory, and Jet Propulsion Laboratory (JPL)), according to interviewees. They also noted that research projects conducted by these laboratories (funded by ERDA) provided important technical input necessary to develop measurement and testing standards, which greatly increased the accuracy and efficiency of PV research by making their results comparable, verifiable, and traceable.

4.1.2 Development and use of JPL specification

Despite the significant improvement of the cell efficiency in late 1970s, early PV modules suffered from low reliability due to the lack of quality standards (Ho and O'Sullivan 2018). Interviewees noted that this is because of not only large-scale and time-consuming R&D required for standardisation but also the lack of commercial perspectives in early stage of technology development. ERDA thus sponsored JPL's Flat-Plate Solar Array (FSA) project from 1975, in order to stimulate the development and widespread use of PV applications and systems (Ho and O'Sullivan 2018). A series of PV module procurement, which required manufacturers to pass a set of prescribed tests to qualify for it, was particularly useful in facilitating the development and diffusion of quality standards developed by JPL, according to interviewees. This government-based standard led to widespread PV terrestrial applications, by helping designers and manufacturers to develop high-quality PV modules, thus ensuring consumer confidence (Ho and O'Sullivan 2018).

4.1.3 ANSI Solar Standards Oversight Committee

With the growth of the PV market and industry, technical committees specifically dedicated to PV were developed in a number of SDOs, including American Society for Testing and Materials (ASTM), Institute of Electrical and Electronics Engineers (IEEE), and Underwriters Laboratories (UL) (Ross and Smokler 1986). Such diverse committee-based standardisation relevant to PV increased potential risks of duplicative standards due to conflicting interests and lack of interactions among them, noted interviewees. In order to support more coordinated standardisation efforts, American National Standards Institute (ANSI) (i.e. an organisation overseeing the development of industry standards in the USA) established Solar Standards Oversight Committee (SSOC), funded by Department of Energy (DOE) (Zerlaut 1996). Allowing division of labour among various SDOs according to their expertise (i.e. ASTM focusing on testing of cells and modules, IEEE focusing on system-related standardisation, and UL focusing on safety issues), it led to more effective standardisation activities in support of PV innovation systems, noted multiple interviewees.

4.1.4. Development and use of ASTM standards

On the basis of their expertise in test methods and specifications, members of ASTM E44 developed numerous standards for

Table 3. Key standardisation activities and relevant policy intervention for PV technology

Key standardidsation activities	Associated systemic problems[1]	Main actors involved	Purpose / goal of policy intervention	(Primary) Type of policy instrument[2]	Year of initiation
Phase I: PV cells & modules					
ERDA / NASA Terrestrial PV Measurement Workshop	• **Act: absence of existing SDOs / lack of capacity** • Ins: lack of common standards • Inf: lack of large-scale R&D required	• ERDA • NASA • JPL, NASA Research Centers, Sandia Laboratory	• Development of common measurement and testing standards	• E: funding workshop to develop standards • E: funding relevant R&D • S: engaging / convening diverse stakeholders	1974
Development and Use of JPL Specification	• Ins: lack of available, widespread standards • Inf: lack of large-scale R&D required	• ERDA • JPL • Sacramento Municipal Utility District	• Development of quality and reliability standards • Implementation of the newly developed standard	• E: funding R&D required for standardisation • E: using standards in public procurement	1975
ANSI Solar Standards Oversight Committee (SSOC)	• Act: SDOs' lack of capacity to coordinate • **Int: lack of interaction among SDOs**	• DOE • ANSI SSOC • ASTM, IEEE, UL	• Effective management of standardisation efforts by various SDOs	• E: funding activities of SSOC to support coordination among SDOs	1976
Development and Use of ASTM Standards	• Ins: lack of widespread standards • Inf: lack of large-scale R&D required	• DOE • NREL	• Development of measurement-related standards • Widespread use of newly developed standards	• E: funding R&D required for standardisation • E: using standards in funding decisions	1982
Phase II: PV applications & systems					
Implementation of UL Standards	• Ins: lack of widespread standards • Ins: lack of relevant rules / legislations • **Inf: lack of knowledge on relevant standards / policies / laws**	• California State Government • California Energy Commission	• Widespread use of newly developed standards	• R: referencing standards in regulations • E: using standards in incentive programs • S: promoting / educating relevant information	Late-1990s
Development and Use of IEEE Standards	• **Act: lack of resources for long-term efforts** • Ins: lack of common standards with high public value • Inf: lack of large-scale R&D required	• DOE, United States Congress • NREL	• Development of interoperability standards • Widespread use of newly developed standards	• R: referencing standards in law • E: funding R&D required for standardisation • E: funding participation in standardisation	Early-2000s
Phase III: Smart Grid systems					
Establishment of NIST Smart Grid Team	• **Act: lack of capacity for broad systems thinking** • Act: absence of relevant SDOs • **Ins: lack of common, widespread standards** • **Int: lack of cross-sectoral interactions**	• DOE, United States Congress • NETL • NIST Smart Grid Team	• Identification of broad standardisation needs in cross-sectoral areas • Development of standardisation system effective for cross-sectoral collaboration	• R: enacting legislations to assign NIST with standardisation roles • E: funding NIST to support cross-sectoral standardisation activities • S: scanning to identify broad standard needs	Mid-2000s
Development of NIST Framework and Roadmap for Smart Grid Interoperability Standards	• **Act: lack of capacity to identify all relevant existing standards** • **Int: lack of cross-sectoral interactions among SDOs / actors**	• DOE • NIST • IEEE. . .	• Widespread use of existing / newly developed standards • Development and improvement of standardisation systems	• E: funding workshops • S: creating / improving systems for effective cross-sectoral standardisation	Late-2000s

(continued)

Table 3. (continued)

Key standardidsation activities	Associated systemic problems[1]	Main actors involved	Purpose / goal of policy intervention	(Primary) Type of policy instrument[2]	Year of initiation
	Inf: lack of knowledge on existing standards across boundaries **Inf: lack of shared understandings**		across sectoral boundaries	S: engaging / convening / coordinating diverse stakeholders S: providing necessary information (framework and roadmap)	
Establishment of Smart Grid Interoperability Panel (SGIP)	Act: absence of capable organisations **Int: lack of cross-sectoral interactions among SDOs / actors** **Inf: lack of common standards database**	NIST SGIP IEEE. . .	Widespread use of existing / newly developed standards Development of sustainable standardisation systems	E: funding to establish SGIP S: creating / improving systems for continued standardisation S: convening / coordinating diverse stakeholders S: identifying, promoting, and maintaining catalog of relevant standards	Late-2000s

[1] Act = Actors' problems, Ins = Institutional problems, Int = Interaction problems, Inf = Infrastructural problems. Newly identified systemic problems due to increasing complexity of modern technologies are highlighted in bold.

[2] R = Regulatory instruments, E = Economic and financial instruments, S = Soft instruments

measurement, testing, calibration, and characterisation of PV cells and modules (e.g. ASTM E892, ASTM E948, ASTM E1039) (Ho and O'Sullivan 2018). Because of the highly infrastructural nature of associated technical R&D, they were mainly researchers from national laboratories, namely Solar Energy Research Institute (SERI, later became National Renewable Energy Laboratory (NREL)), run by public research funding (McConnell 2006). Allowing more accurate and reliable evaluation of research results (Ho and O'Sullivan 2018), ASTM standards were often used to help DOE and other public agencies make project funding decisions, according to interviewees. They noted that this resulted in the widespread use of measurement and testing standards across the industry, thus influencing research directions and leading to significant improvements of cell performances in 1980s.

4.2 Phase 2: standardisation of PV applications and systems (1990–2005)

4.2.1. Implementation of UL standards

With the development of on-grid PV applications and systems, safety standards relevant for PV modules as well as other electronic components required in PV systems—such as inverters, batteries, and power controllers—were critical to increase user confidence in the new technology being connected to their grids (Ho and O'Sullivan 2018). In order to facilitate the implementation of appropriate UL standards, government introduced various regulatory and economic instruments, recalled multiple interviewees. For example, requirements of UL 1741 (i.e. standard testing method for inverters, converters, and controllers for use in independent power systems) had to be met by PV systems to be connected to publicly-owned utilities according to Rule 21 (i.e. California's safety regulations). Certification to UL 1741 was also required for utilities to qualify for public incentive programmes (e.g. Million Solar Roofs Programme as part of California Solar Initiative). Information on such policies and regulations were then promoted through soft instruments, such as guidelines published and distributed by public agencies (e.g. the California Energy Commission) (Pennington et al. 2008). These policy efforts led to the widespread implementation of quality and reliability standards for on-grid PV systems, significantly increasing confidence of utility companies which in turn led to the growth of on-grid PV industry (Ho and O'Sullivan 2018).

4.2.2 Development and use of IEEE standards

The increasing number of distributed generators (e.g. using PV and wind) connected to power grids also called for IEEE SCC21 to develop IEEE 1547, standard for interconnecting distributed resources with larger electric power systems (Ho and O'Sullivan 2018). Staff from NREL actively participated in the committee by not only providing their R&D results as technical input into standards writing but also acting as committee chairmen or secretaries, according to interviewees. They added that such activities were necessary to address *actors' problems*, as private companies were often reluctant to devote their resources into long-term efforts of standardisation that provides no immediate results. IEEE 1547 was then cited in the US Federal Energy Policy Act, which mandates its use in the development of interconnection services, because of the high public value of achieving successful linkages within the nation's energy infrastructure (Basso 2014). By allowing advanced communications among various products and subsystems, this national compatibility and interface standard provided a common platform for innovation actors to perform further entrepreneurial experiments, noted multiple interviewees.

4.3 Phase 3: standardisation of Smart Grid systems (2005–15)

4.3.1 Establishment of NIST Smart Grid Team

The advancement of ICT has led to the emergence of Smart Grid in late 2000s; as an advanced power grid integrating varieties of ICT with the existing grid, it not only reduces inefficiencies in energy delivery but also allows more effective management of distributed generators (such as PV and wind) and storage of electric power (NIST 2010). Needs for appropriate and readily available standards were often identified as a critical factor for the success of Smart Grid during DOE's preliminary studies (e.g. Grid 2030, Modern Grid Initiative conducted by National Energy Technology Laboratory (NETL)) (Updegrove 2009). As Smart Grid is a complex system of systems integrating a vast number of devices, products, processes, and subsystems across traditional technological or industrial boundaries (e.g. energy and ICT), appropriate system-level standards were critical to ensure their interoperability and data exchanges, as well as their quality, safety, and security (NIST 2014). Yet, standardisation needs in such emerging cross-sectoral areas (and potential policy needs to support it) could only be identified by public agencies with a broad systems thinking, while individual actors or organisations tend to be confined in their narrow areas of expertise due to fragmented understanding and lack of available resources.

The development of Smart Grid standards also called for cooperation and collaboration of a broad spectrum of stakeholders across diverse domains and technological boundaries (including utility companies, equipment suppliers, system integrators, product developers, end-users, SDOs, and government agencies) (NIST 2010). While their standardisation works used to be often viewed as separate activities, effective collaboration became critical to avoid risks of duplicative (or even contradicting) standards, which may lead to inefficiency and market confusion. For examples, interviewees noted an example of smart modules (i.e. PV modules connected with other electronic devices for better communication and control), whose standardisation required technical expertise of both PV modules and electronic systems. However, there were neither existent organisations capable of engaging and coordinating such diverse stakeholders nor enough interactions between them to support the collaboration across boundaries organised around the existing division of labour, noted interviewees.

In order to address such gaps, the Energy Independence and Security Act of 2007 assigned the National Institute for Standards and Technology (NIST) the 'primary responsibility to coordinate development of a framework... to achieve interoperability of Smart Grid devices and systems' (NIST 2010: 7). The NIST's reputation as an 'honest broker' (i.e. impartial, technically-knowledgeable third party) that works collaboratively with industry and other government agencies made it appropriate to lead public–private collaboration required for cross-sectoral standardisation activities. On the basis of this legal framework, NIST Smart Grid Team was established to facilitate the development and implementation of appropriate standards necessary for the deployment of Smart Grid (NIST 2010).

4.3.2. Development of NIST Framework and Roadmap for Smart Grid Interoperability Standards

In order to help guide and align standardisation activities in this emerging complex system with multiple technology bases, NIST Smart Grid Team has developed a three-phase plan; the first phase involved engaging diverse stakeholders in participatory public processes (NIST 2010). A series of workshops and high-level meetings were organised to gather various members of the community from a wide variety of perspectives (including transmission and distribution, markets, storage, smart buildings, businesses, finance, and standardisation) and facilitate their communications (Ho and O'Sullivan 2017). According to interviewees, these helped identify common visions of Smart Grid and articulate shared understanding of its main building blocks (and their architecture), which were critical for cross-sectoral collaborations among diverse stakeholders with different interests and backgrounds.

Public workshops also identified an initial set of existing interoperability standards that could be immediately applied, or were expected to be available in the near future, to meet Smart Grid needs (NIST 2010). Published as a list of 'identified standards' after a public review, they helped relevant actors learn useable standards distributed across various SDOs (thus difficult to identify those outside the scope of their usual expertise), so leading to their widespread use, noted interviewees.

In addition, NIST developed and published *NIST Framework and Roadmap for Smart Grid Interoperability Standards*, which provided architectural frameworks to identify remaining standardisation needs and a roadmap for initial action plans to address them (NIST 2010). Additional standards requirements were identified by analysing various use cases and evaluating them against the list of existing standards; Priority Action Plans (PAPs) were then developed, including details such as specific organisations tasked and time plans (Ho and O'Sullivan 2017). All these activities enabled rapid pace of standardisation works, by facilitating cross-sectoral collaborations among diverse SDOs and relevant stakeholders, according to interviewees.

4.3.3 Establishment of Smart Grid Interoperability Panel

The next phase of the NIST's plan involved launching a formal public–private programme to facilitate continued coordination, acceleration, and harmonisation of SDOs' efforts for the timely availability of appropriate standards as the complex system of Smart Grid evolves (NIST 2010). Although public workshops with a large number of participants were useful to build initial consensus and increase awareness on the importance of standardisation, interviewees recalled them extremely time– and resource-consuming. NIST Smart Grid Team thus helped establish Smart Grid Interoperability Panel (SGIP) forum, a more structured system of cross-sectoral standardisation required for additionally needed standards (NIST 2014). In order to allow broad and inclusive participation by all key players across the industry and ensure that no single interest dominates over the others, twenty-two stakeholder categories have been designed in the SGIP governing board; the SGIP staff paid significant attentions to address perspectives of all stakeholder members involved in the development and operation of Smart Grid, according to interviewees. The SGIP thus provided a structured platform for ongoing identification of additional standard gaps, PAP prioritisation, and the construction of timelines for addressing remaining gaps (NIST 2014).

SGIP was also responsible for producing, maintaining, and promoting the Catalog of Standards, a compendium of standards related to Smart Grid (NIST 2014). Such arrangements were necessary because the complex, convergent, and systems-like nature of Smart Grid led to the proliferation of relevant standards and their (often unexpected) relationships, thus increasing challenges for their management and maintenance in response to technical changes, noted multiple interviewees. As existing SDOs (often focusing on particular technical or industrial areas) lacked holistic and comprehensive perspectives for such cross-sectoral management, there were risks of incompatible (or even conflicting) standards, potentially inhibiting innovation. Additional *interaction problems* due to strong ties around outdated standards could also prevent relevant actors to adopt new, revised standards. In addition, *infrastructural problems* could exist due to the lack of widely available knowledge among the community on up-to-date standards outside the scope of their usual standards directory, hindering their broad diffusion. Addressing increased risks of such systemic problems, Catalog of Standards was highlighted by multiple interviewees as a useful tool that supports effective management and maintenance of a large stock of standards relevant to complex systems of Smart Grid.

In 2013, the SGIP has been restructured as SGIP 2.0, transitioning from a strictly government-funded organisation to a self-sustaining, non-profit entity with the majority of funding coming from industry stakeholders (Schneiderman 2015). Twenty-two stakeholder categories have been replaced with five interest categories (one of which includes governmental entities), which are framed like many other deliberative industry organisations where consensus-based solutions to industry issues are considered, noted an interviewee.

5. Discussion

Having outlined the evolving variety of innovation problems related to standardisation and corresponding policy actions adopted in the case study, this section reflects on how the SI-based frameworks offer new insights and understanding of the rationales for diverse and increasing policy needs, and the potential toolbox of policy instruments, relevant to standardisation of cyber-physical smart systems.

5.1 Increasingly diverse systemic problems associated with standardisation

The case study shows that dimensions and elements of the SI-based frameworks (discussed in Section 2.3) allow for more detailed and structured analyses of the systemic problems associated with standardisation, highlighting the progressively complex and diverse sources of such problems. Ineffective standardisation activities may result from *actors' problems* (e.g. absence of existing SDOs, individual actors' lack of capacity to participate in standardisation), *institutional problems* (e.g. lack of relevant legislations), *interaction problems* (e.g. strong ties between existing participants), or *infrastructural problems* (e.g. lack of widely available knowledge on existing standards). Such diversity and evolving complexity largely reflect the complex and dynamic nature of standardisation in technological innovation systems, in terms of various roles and functions, different types of technologies and innovation activities involved, and diverse modes of coordination, as highlighted by Ho and O'Sullivan (2018).

The study particularly highlights greater systemic problems due to the unprecedented level of complexity in modern technologies, as standards with a high level of technical details are required to support even early-stage innovation of emerging technologies, where there is limited knowledge available. Consistent with recent academic literature (e.g. Blind and Gauch 2009), the case study shows that standardisation of terminology, measurement methods, and testing procedures in early stages of R&D is important to facilitate communication and collaboration among researchers from different organisations. However, there are *infrastructural problems* due to the lack of enabling technologies required for R&D (so called 'infratechnologies' as discussed by Tassey 1982, 2000), as well as *actors' problems* due to the lack of appropriate SDOs, resulting in fragmented knowledge dispersed across the wide community of relevant stakeholders with low levels of interactions between them. In addition, individual private-sector actors are neither capable of initiating collective industrial initiatives nor willing to devote significant financial and human resources to standardisation, which requires long-term effort with no guarantee of return on investment in what are typically immature industrial domains. Such additional risks associated with *actors' problems* with standardisation in early stages of emerging technologies have received only limited attention in the existing literature.

Even after relevant SDOs have been established with the growing market, there arise increased risks of systemic problems associated with standardisation, as technology develops and its application systems become increasingly complex, convergent, and systems-like in nature. The case study in this article highlights that many problems observed in earlier stages of PV technology emergence are significantly exacerbated by additional *interaction* and *infrastructural problems* that arise from the evolution of standardisation landscapes in response to the transition into complex systems of Smart Grid.

Firstly, insufficient interactions among participants of standardisation committees across existing sectoral boundaries are recently being highlighted in the case study. As new technologies continuously (and increasingly) emerge and get integrated into complex, cross-sectoral systems, effective standardisation requires new stakeholder perspectives from outside the current members' main expertise (e.g. new PV materials such as organic PV materials and other components required for new applications such as automotive, as highlighted by interviewees). However, strong network and relationships among current members increase challenges in identifying and engaging diverse participants from broader stakeholder groups, particularly across traditional boundaries organised around the existing division of industrial value chain.

Secondly, there are increased problems due to the lack of interactions among various SDOs, which exist mainly because of their conflicting interests. Partly observed in early stages of PV technology, these problems are exacerbated in complex smart systems where there are increasing, unexpected relationships among standards developed by different SDOs. Coordination and collaboration among diverse SDOs across existing sectoral and industrial boundaries are thus necessary, in order to not only develop common vision and understanding with a broad cross-sectoral systems thinking but also manage a large number of interrelated standardisation projects in a coherent manner. Although Solar Standards Oversight Committee (SSOC) have been organised to facilitate such coordination and alignment in early stage of PV development, greater systemic problems due to increased complexity of PV systems have not been properly identified, resulting in some duplicative, or even conflicting, standards (e.g. IEEE 1547 and UL 62109–1, both addressing safety issues of PV systems), noted multiple interviewees. They recalled that these resulted in inefficiency and confusion, as well as significantly increased production costs, so hampering innovation and development of PV industry.

Thirdly, the case study highlights increased risks of *infrastructural problems*, because of greater 'public good' nature of standards as crucial knowledge infrastructure in ever-growing complex systems such as Smart Grid. In addition to infratechnologies required for the development of standards (as identified by previous literature, e.g. Tassey 1982, 2000), these standards are essential information infrastructure themselves due to powerful network effects and externalities observed in complex systems of networked ICT. Although their importance as critical shared infrastructure has been somewhat discussed in previous studies (e.g. Branscomb and Kahin 1995; Swann 2010), it is ever more increasing in systems with

Table 4. Emerging roles of government in standardisation of diverse smart systems across the world

Smart systems	Country	Emerging roles of government				References
		Convenor	Coordinator	Educator	Observer	
Smart Grid	US	Engaging diverse stakeholders	Coordinating diverse stakeholders	Providing information to diverse users	Monitoring to identify new standardisation needs	Current case study
	Japan	Establishing relevant working group		Introducing international standardisation roadmap		(Mah et al. 2013)
Smart Transportation	Germany	Engaging diverse stakeholders	Coordinating diverse standardisation activities	Introducing standardisation roadmap		(Ho & O'Sullivan 2017)
Smart Manufacturing	Germany	Engaging diverse stakeholders	Coordinating diverse stakeholders & SDOs	Introducing standardisation roadmap	Monitoring to identify needs for cross-domain strategies	(Ho & O'Sullivan 2017)
	US	Sponsoring workshops to engage diverse stakeholders	Coordinating stakeholders across diverse technical areas	Providing information / education on relevant standards		(Gallaher et al. 2016; Hannah et al. 2018)
Smart City	UK	Establishing new platforms for collaboration	Coordinating between private and public sectors	Providing guidance / information on standards / regulations	Identifying standard needs beyond the individual scope	(Nohrová 2014)

unprecedented levels of complexity and interdisciplinarity. Standardisation allows physical connection and interoperability between a vast number of components and subsystems that are based on different technology bases. It also provides critical linkages supporting interactions among multitudes of actors across traditional industrial and sectoral boundaries, thus facilitating overall innovation processes. Standardisation thus plays essential roles as knowledge infrastructure in complex smart systems, suggesting potentially increased risks of *infrastructural problems* when appropriate standards are not in place.

Lastly, the case study identifies increasing risks of *infrastructural problems* due to the lack of appropriate information about relevant, up-to-date standards, as these information are also important knowledge infrastructure with greater 'public good' nature in cyber-physical smart systems. Because of complex, unexpected relationships between a large stock of standards from different domains and disciplines, individual actors may lack capacity to identify all standards relevant to their activities, particularly those outside their usual directory. A single SDO also lacks ability to maintain up-to-date databases of all interrelated standards—by following their development, revision, and removal in response to technical changes—and provide relevant information to the wide community of potential users. There are thus greater risks of incompatible or outdated standards being used, inhibiting the functioning of overall innovation systems. Such problems are becoming even more significant, as many standards are recently being developed by ad-hoc organisations whose activities are difficult to keep track of, noted an interviewee.

In summary, the case study demonstrates increasingly diverse risks of systemic problems associated with standardisation in modern technological innovation systems, as opposed to previous literature that often identify 'lack of appropriate standardisation' as a single innovation bottleneck. It particularly highlights *actors' problems* in early stages of technology R&D, as well as *interaction* and *infrastructural problems* during the transition to complex systems of Smart Grid. The latter is because of increasing interactions of actors (i.e. both SDOs and participants of standardisation committees) required across traditional sectoral boundaries, as well as growing importance of standardisation as critical knowledge infrastructure with greater 'public good' nature. By allowing such detailed analyses of various systemic problems associated with standardisation, the SI-based frameworks (Ho and O'Sullivan 2018; Wieczorek and Hekkert 2012) thus provides greater insights into rationales for recently growing policy needs with the transition to cyber-physical smart systems.

5.2 Roles of government to support standardisation in smart system innovation

The case study shows that government increasingly plays broad and evolutionary roles in order to address diverse and increasing systemic problems associated with standardisation of Smart Grid systems. A review of recent studies on various smart systems (e.g. Smart Manufacturing, Smart Transportation, and Smart City) also demonstrates more active roles of governments across the world to ensure timely and effective standardisation of such complex cyber-physical systems (summarised in Table 4). In particular, emerging roles of government as convenor, coordinator, educator, and observer are highlighted from both this case study and the review of other studies. This confirms fundamental transformations of government from being providers and regulators to being coordinators and facilitators (as suggested by recent policy literature, e.g. Jordana and Levi-Faur 2004) in the context of standardisation.

Firstly, government plays an important role of a convenor, initiating standardisation efforts by engaging all relevant stakeholders with a wide variety of expertise on board. This is particularly significant during the transition to cyber-physical smart systems, when *actors' problems* (due to the lack of appropriate SDOs) are exacerbated by *interaction problems*, resulting in increased challenges for

Table 5. Policy instruments to address systemic problems associated with standardisation

Types	Policy instruments[1]	Systemic problems associated with standardisation[2]			
		Actors' problem	Institutional problem	Interaction problem	Infrastructural problem
Regulatory instruments	Referencing standards in laws / regulations		X		
	Developing legal frameworks for cross-sectoral standardisation systems	X		X	X
Economic and financial instruments	Funding workshops to develop standards in early stages of R&D	X	X		
	Funding R&D required for standardisation				X
	Funding activities to participate in standardisation	X			
	Funding activities for coordination of various SDOs (particularly across sectors)	X		X	
	Using standards in making decisions for funding programs		X		
	Using standards in public procurement		X		
Soft instruments	**Engaging / coordinating diverse stakeholders / SDOs**	X		X	
	Promoting / educating info. of relevant standards / laws / policies			X	X
	Identifying / maintaining databases of relevant standards	X	X	X	X
	Scanning to identify broad standardisation needs	X		X	
	Developing new organisations / frameworks to promote cross-sectoral standardisation activities	X		X	

[1] Only examples of policy instruments illustrated in the case study are shown. Those particularly targeting to address recently increasing systemic problems in complex smart systems are highlighted in bold.

[2] Only main systemic problems specifically aimed by particular policy instruments are marked.

engaging stakeholders outside the scope of their existing networks (as discussed in Section 5.1). Government or public agencies thus often intervene to facilitate the development of new platforms for effective cross-sectoral standardisation among such diverse participants with broad backgrounds. They can either act as convenors themselves by initiating workshops (as in the case study) or provide appropriate resources to relevant organisations (e.g. industry consortia) to promote their convening activities (e.g. Hannah et al. 2018; Nohrová 2014).

Secondly, there are growing roles for government and public agencies as coordinators to mitigate *interaction problems* associated with coordination and collaboration among various SDOs relevant to increasingly complex smart systems (e.g. Ho and O'Sullivan 2017). Bringing more holistic and systemic perspectives than SDOs that often focus on different technological and industrial domains, they can not only coordinate and align various cross-sectoral standardisation activities but also organise relevant initiatives that cut across existing boundaries (Wessner 2011). Although consortia self-organised by private actors sometimes emerge to conduct such coordination and collaboration activities (e.g. Solar America Board for Codes and Standards, PV Standards and Codes Forum, and PV Manufacturing Consortium), they are neither as effective nor sustainable without support from public funding, noted interviewees. Various modes of coordination, including interagency working groups, task forces, and fast-track action committees, can be adopted to facilitate cross-sectoral standardisation of cyber-physical smart systems.

Thirdly, government or other public organisations can act as educators, providing information about certain standards, as well as relevant policies and regulations, to a diverse community of users. By creating and managing database systems (e.g. SGIP's Catalog of Standards) or publishing relevant information in roadmaps (e.g. Ho and O'Sullivan 2017; Mah et al. 2013), they can facilitate the implementation and diffusion of appropriate standards in a timely manner, so reducing risks of incompatible or outdated standards being used. This is particularly important as systems evolve to become more complex and convergent, leading to greater *interaction* and *infrastructural problems* in identifying and maintaining a large stock of relevant standards with unexpected interdependencies between them (as discussed in Section 5.1). Only public actors with a systems perspective have capacity to monitor interrelated standardisation activities in various SDOs, manage database across existing sectoral boundaries, and provide appropriate education to the public.

Lastly, these broad and growing roles of government to ensure effective evolution of standardisation frameworks with the transition to complex cyber-physical smart systems imply their additional role as an observer, continuously monitoring to identify and assess new opportunities for their engagement on an ongoing basis. Scanning recent trends and events across various technological domains, application markets, and industrial sectors can help identify emerging standardisation needs in cross-sectoral areas, which require a systems thinking beyond the scope of individual SDOs (Nohrová 2014). It can also ensure early policy supports to drive standardisation efforts in emerging technologies where there are not only fragmented understanding dispersed across the industry but also the lack of interests among private actors, so promoting further technological innovation and development.

5.3 Growing use of policy instrument mixes

The case study shows that these broad and evolutionary roles of government are performed by a variety of policy actors operating at varying levels of governance (i.e. individual, group, and organisational actors, whether regional or domestic). While government departments such as ERDA and DOE mobilise their resources to achieve policy objectives, public agencies such as NASA, NREL, and NIST receive and utilise them to achieve policy outcomes. They perform various policy actions to target changes of behaviour of diverse actors, including private actors such as ASTM and IEEE, as well as particular groups or individuals at public agencies, such as staff at JPL and NIST Smart Grid Team.

Table 5summarises various policy instruments that are actually designed and introduced by these policy actors to address diverse systemic problems associated with standardisation. Categorised according to the general threefold typology suggested by Borrás and Edquist (2013), it represents a comprehensive list of various policy instruments supporting effective standardisation. The list particularly highlights growing uses of soft instruments to address increasing *interaction* and *infrastructural problems* associated with standardisation of cyber-physical smart systems. These are consistent with recent standardisation literature and practice (e.g. Blind 2016; NIST 2011), as well as innovation policy literature (e.g. Borrás and Edquist 2013) that denote increasing uses of soft instruments to address problems that previous regulatory and economic instruments cannot do properly because of the complex nature of innovation.

The study also demonstrates the growing use of a ‘mix’ of instruments by various policy actors with multiple policy objectives to address a combined set of systemic problems, confirming recent innovation policy literature adopting the policy mix concept (e.g. Flanagan et al. 2011; Rogge and Reichardt 2016). Because of the complex and multiple nature of problems associated with standardisation, a combination of policy instruments need to be designed and implemented at varying levels. Although they should be designed to address specific problems in particular contexts, dissecting and analysing diverse policy instruments may provide greater insights into how to design appropriate policy actions to promote timely and effective standardisation in support of innovation.

In particular, the framework by Ho and O’Sullivan (2018) helps analyse these policy instruments against various dimensions of standardisation (e.g. types of standards, their impacts on innovation, and timing) in a systematic way. Different policy instruments are particularly relevant to different dimensions of standardisation and their categories, as summarised in Table 6. During the emergence of new technology, government adopts diverse policy instruments to initiate standardisation efforts by engaging relevant stakeholders and establishing necessary standardisation frameworks. Many economic instruments have been introduced in early stages of PV technology, in order to support timely standardisation as well as required R&D to develop them. Regulatory instruments by referencing in laws or regulations are often used when standards are critical to ensure quality and reliability of products or systems introduced in the market. As their application systems become more complex, diverse soft instruments have been introduced to support broad standardisation activities but particularly focusing on compatibility or interface standards relevant to systems with multiple technology bases. They are increasingly developed in consortia-like committees, ensuring cross-sectoral collaboration among diverse stakeholders involved.

5.4 Practical use of the integrated framework to inform policymakers

As discussed earlier, dimensions and elements captured in the SI-based frameworks (presented in Section 2.3) allow problem-oriented analyses of standard-related bottlenecks in current innovation systems under study, providing a strong evidence base for appropriate policy actions that precisely target structural elements causing these problems. They thus amount to a novel integrated framework that can be used by policymakers in identifying where, why, and how policy intervention can be used to promote timely and effective standardisation in practice. Needs for such systematic analyses are growing as the transition to complex smart systems with unprecedented levels of complexity, interdisciplinarity, and system-like nature calls for greater roles for government to address increased risks of systemic problems (particularly *interaction* and *infrastructural problems*), as observed from the case study. It is carefully suggested that problems of duplicative standards in multiple SDOs that hindered the PV development could have been avoided if guided by the proposed, SI-based framework to devise appropriate policy actions.

It is, however, to be noted that because of path-dependent and evolutionary characteristics of the SI perspective, the proposed framework is less prescriptive about optimal policy instruments to design and operationalise (Dodgson et al. 2011; Laranja et al. 2008). Rather than immediately being able to provide definitive and highly-specified policy recommendations, it can only inspire or imply consideration of particular kinds of intervention (Borrás and Edquist 2013). Nevertheless, as the framework is built on a practical roadmapping framework that enables participatory processes to engage multiple experts and facilitate structured discussion among them, the framework can be readily implemented by policymakers to explore and contribute to more clearly-justified and well-specified policy intervention. Policymakers can thus be adaptive to design well-informed, context-specific policy instruments that may be able to mitigate certain systemic problems identified from the framework (Chaminade and Edquist 2010).

Despite the need for policymakers to be adaptive and responsive, it is still possible to identify a toolbox of broader categories of policy instruments, which could help them design appropriate policy actions (see Table 7). Diverse examples of policy instruments from the case study are categorised according to their purpose or intended effects that contribute to achieving high-level policy objectives, in addition to the general threefold typology developed by Borrás and Edquist (2013). While the overall goal of all policy intervention would be to promote effective standardisation in support of innovation, it can be achieved by different policy instruments with different strategic purposes, depending on specific policy objectives. For example, some policy instruments in early stages of PV technology aimed to stimulate standardisation activities so that new, appropriate standards are developed, whereas other instruments aimed to promote implementation and use of particular standards that have already been developed. They can thus be categorised into supply– and demand-side instruments, influencing the supply of and demand for standardisation, respectively.[3] The case study also shows increasing uses of policy instruments with more systemic purposes, as the transition to Smart Grid increases risks of systemic problems that cannot be addressed by simply promoting the development or use of particular standards. Systemic instruments of standardisation

Table 6. Policy instruments and relevant dimensions of standardisation

Types	Policy instruments	Dimensions of standardisation[1]			
		What	Why	When	How
Regulatory instruments	Referencing standards in laws / regulations	Mainly product, system	Quality / reliability standards	During technology development	National standard
	Developing legal frameworks for cross-sectoral standardisation systems	All, but particular relevance to systems with multiple technology bases	All, but particular relevance to compatibility / interface standards	During the emergence of new technology or its application systems	Committee, government-based modes
Economic and financial instruments	Funding workshops to develop standards in early stages of R&D	Mainly science base	Terminology, measurement / characterisation standards	During early technology development	Technical report, government-based mode
	Funding R&D required for standardisation	Most technology related activities	All relevant	During (early) technology development	Committee, government-based modes
	Funding activities to participate in standardisationUsing standards in making decisions for funding programs	All relevant	All relevant	During technology development	Committee-based mode
	Funding activities for coordination of various SDOs (particularly across sectors)	All, but particular relevance to systems with multiple technology bases	All, but particular relevance to compatibility / interface standards	During the emergence of new technology or its application systems	Committee-based mode (increasing roles of consortia)
	Using standards in public procurement	Mainly product / application	Mainly quality / reliabilitystandards	During early technology development	Government-based mode
Soft instruments	Engaging / coordinating diverse stakeholders / SDOs	All relevant	All, but notably terminology standards	During the emergence of new technology or its application systems	Often technical report / workshop agreement
	Promoting / educating info. of relevant standards / laws / policiesIdentifying / maintaining databases of relevant standards	All relevant	All relevant	During the development of technology and relevant (complex) systems	Committee-based mode (increasing roles of consortia)
	Scanning to identify broad standardisation needsDeveloping new organisations / frameworks to promote cross-sectoral standardisation activities	All, but particular relevance to systems with multiple technology bases	All, but particular relevance to compatibility / interface standards	During the development of complex systems	Committee-based mode (increasing roles of consortia)

[1] What = *what* technology elements and innovation activities are relevant to standardisation, Why = *why* standardisation is needed, When = *when* to be standardised, How = *how* to standardise. Only dimensions of standardisation with particular relevance to the case study are highlighted. See Ho & O'Sullivan (2018) for details and exemplar categories of these dimensions.

(inspired from Rogge and Reichardt's (2016) concept of systemic instruments of innovation) are thus increasingly introduced to catalyse, support, and manage the interplay and interactions between demand– and supply-sides of standardisation at a more holistic level. As distinctions of these categories are not always clear-cut, policy instruments in Table 7 are put according to their primary purpose and type.

When using the proposed framework and the above toolbox, it is also important to consider socio-political and historical contexts in which policy instruments operate, because of the path-dependency and dynamic evolution of standardisation systems. As important institutions in which various SDOs and relevant actors are embedded, standardisation systems vary considerably according to historically rooted, and often nationally distinct, institutional trajectories (Zysman 1996). Different national governments thus have different approaches to standardisation, with different meta-rationales (i.e. high-level philosophies about the proper modes and limits of government actions, Laranja et al. 2008) for policy intervention (Borraz 2007; Gao et al. 2014). For example, countries with liberal market economies (e.g. the USA) encourage a highly-decentralised, even fragmented, standardisation system among individual-oriented professional societies, whereas other countries (e.g. Germany and Japan) adopt a more coordinated approach within particular (usually public) SDOs (Tate 2001). Highlighting such institutional and evolutionary characteristics of standard-related policies, existing literature reaffirm that the SI perspective provides a more appropriate theoretical basis than the neoclassical approach, which ignores the institutional aspect of innovation (Bach and Matt 2005).

6. Conclusion

This article explores the evolving roles of government in supporting timely and effective standardisation of complex technological

Table 7. Typology of policy instruments to support effective standardisation

Purpose Types	Supply-side instruments (to support development of new standards)	Demand-side instruments (to promote wide uses of existing standards)	Systemic instruments (to facilitate interactions between development/ supply and use/ demand of standards)
Regulatory instruments	• Developing legal frameworks for national standardisation systems	• Referencing standards in laws / regulations	• Developing legal frameworks for cross-sectoral standardisation systems
Economic and financial instruments	• Funding workshops to develop standards • Funding R&D required for standardisation • Funding participation in standardisation activities	• Using standards in public procurement • Using standards in decision-making for R&D funding / incentive programs	• Funding workshops for coordinating various SDOs' standardisation efforts • Funding organisations for managing cross-sectoral standardisation activities
Soft instruments	• Engaging / coordinating diverse stakeholders • Scanning to identify broad standardisation needs	• Identifying / promoting relevant standards • Educating laws / policies / information relevant to particular standards	• Maintaining a database of relevant standards • Creating organisations / frameworks for improved cross-sectoral standardisation activities • Providing education / trainings on standardisation to the wider public

systems. This not only is an increasingly important area of innovation policy but also faces new challenges with the recent transition to ever more complex cyber-physical smart systems. In particular, there is an increasing policy interest in opportunities to support effective standardisation of complex smart systems, as they provide important sources of competitive advantages for economic development, as well as great societal impacts by pervading many critical aspects of national infrastructure (e.g. Smart Grid, Smart Transportation, and Smart Manufacturing). Despite such importance and urgency, existing policy-focused studies generally suggest only limited roles of government in standardisation. This is mainly owing to the limitations of current academic conceptualisations of standardisation in understanding the innovation dynamics of progressively complex systems, which in turn present significant challenges in identifying appropriate roles of government.

In order to address such limitations of existing literature, this article presents a novel integrated framework based on the SI perspective for more systematic and comprehensive analyses of variety and complex dynamics associated with potential standard-related problems within innovation systems and corresponding roles of government to address them. It is developed by bringing together dimensions and concepts from: a systematic framework for identifying potential standardisation needs to enable technological innovations—by addressing innovation bottlenecks—(Ho and O'Sullivan 2018); and a policy framework for analysing systemic problems to identify appropriate policy instruments (Wieczorek and Hekkert 2012). The integrated framework can thus be used for detailed analyses of (i) structural elements of innovation systems that result in systemic problems related to standardisation (i.e. actors, institutions, interactions, and infrastructure); (ii) rationales and roles for government to address those problems (e.g. development or widespread use of appropriate standards); and (iii) appropriate mix of policy instruments to achieve these policy goals (e.g. various regulatory, economic and financial, and soft instruments).

A historical case study of PV technology (from early R&D to its recent integration into complex systems of Smart Grid) is then presented, highlighting a variety of policy instruments introduced by diverse policy actors to address an evolving set of systemic problems associated with standardisation. The case study not only illustrates values of the framework but also provides a more thorough understanding of rationales for recently increasing and diverse policy needs in standardisation. The transition to cyber-physical smart systems, which involve unprecedented levels of complexity and interoperability requirements, has led to the growing importance of standardisation as critical knowledge infrastructure with strong 'public good' nature, as well as high levels of interactions required across traditional sectoral boundaries. Such increased risks of *interaction* and *infrastructural problems* call for evolving roles for government, particularly those as convenor, coordinator, educator, and observer, in standardisation of complex smart systems. Increasing uses of soft instruments with a systemic approach (e.g. engaging diverse stakeholders, promoting relevant standards, and maintain standards database) are thus being observed, as also proved in a review of recent studies on various smart systems (e.g., Smart Manufacturing, Smart Transportation, and Smart City). In addition, novel toolbox, summarising a variety of policy instruments that practitioners can adopt to promote effective standardisation, is developed from the case study.

Hence, the study provides policymakers with more practical guidance to determine where, why, and how policy intervention is needed for effective standardisation of complex cyber-physical smart systems by providing a more complete picture of the system and standard-related problems. It is, however, to be noted that the current framework only reveals *potential* target areas for policy intervention, as the complex-evolutionary perspective of IS does not self-evidently provide definitive and highly-specified policy recommendations. Further research is thus needed to validate exactly whether and which specific policies *should* be implemented to promote effective standardisation and to weigh-up the inevitable trade-offs and tensions between various policy options. The concept of 'innovation policy mix' should also be carefully considered in future standard-related policy research, as the case study shows that diverse policy instruments may be adopted by various policy actors with multiple policy objectives. There are further research opportunities for multiple case studies in diverse contexts, in order to provide richer evidence for policymakers to make more informed decisions regarding their engagement and allocation of resources. In particular, in-depth case studies in other areas of modern smart systems may identify additional challenges and emerging practices regarding standardisation of complex technological systems (such as the role of industry consortia).

In summary, this article makes significant contributions to the domain of innovation policy research by proposing an integrated framework to systematically analyse evolving roles of government in standardisation to support increasingly complex innovation systems. This is a critical area of future research in innovation policy, which will become ever more important in the era of cyber-physical smart systems.

Notes

1. The term *cyber-physical 'smart systems'* refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities (Baheti and Gill 2011), by incorporating a wide varieties of networked sensing, digital computing, and communication technologies, to perform smart actions (Ho and O'Sullivan 2017).
2. For example, asymmetric information is considered by the SI perspective as an integral and necessary aspect of innovations, promoting diffusion and further development of new knowledge; whereas the neoclassical approach, based upon assumptions of equilibrium and perfect information, identifies it as market failure that need to be eliminated by policy intervention.
3. They are similar to, but not to be confused with, supply– and demand-side instruments of innovation (as customary in existing literature, e.g. Edler and Fagerberg 2017).

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Appendix

Table A.1. Profiles of experts interviewed in the case study.

Expert #	(Type of) organisation	Area of expertise in standardisation	Interview date	Note
1	Private company	PV cells and modules	3 May 2012	Via phone (preliminary)
2	University	PV applications and systems	9 May 2012	Via phone (preliminary)
3	University	PV applications and systems	10 May 2012	Via phone (preliminary)
4	Private company	PV cells and modules	10 May 2012	Via e-mail (preliminary)
5	SDO	PV cells and modules	14 May 2012	Via e-mail (preliminary)
6	SDO	PV applications and systems	18 May 2012	Via e-mail (preliminary)
7	NIST	Smart Grid	7 March 2014 25 March 2014 19 August 2014	Via phone (preliminary)
8	NIST	Smart Grid	13 March 2014	Via phone
9	NIST	Smart Grid	19 August 2014	Focus-group
10	NIST	Smart Grid	19 August 2014	Focus-group
11	NIST	Smart Grid	19 August 2014	Focus-group
12	NIST	Smart Grid	20 August 2014	
13	Private company	PV applications and systems, Smart Grid	24 February 2015 3 June 2015	
14	Private company	PV applications and systems	25 February 2015	
15	Private company	PV cells and modules	25 February 2015	
16	Private company	PV cells and modules	25 February 2015	
17	NREL	PV cells and modules	26 February 2015	
18	Private company	PV applications and systems	26 February 2015	
19	NREL	PV cells and modules	27 February 2015	
20	NREL	PV cells and modules	27 February 2015	
21	Consulting company	PV cells and modules	2 March 2015	
22	NREL	PV cells and modules	3 March 2015	
23	Consulting company	General	4 March 2015	
24	NREL	PV applications and systems, Smart Grid	5 March 2015	
25	NREL	PV cells and modules	6 March 2015	
26	NREL	PV cells and modules	7 March 2015 15 June 2015	
27	NREL	PV cells and modules	7 March 2015	
28	NREL	PV cells and modules	10 March 2015 17 June 2015	
29	Private company	PV cells and modules	13 March 2015	
30	Private company	PV cells and modules	13 March 2015	
31	Private company	PV applications and systems	16 March 2015	Via phone
32	Industry association	PV applications and systems, Smart Grid	18 March 2015	
33	SDO	PV cells and modules, PV applications and systems	19 March 2015 28 April 2015 15 June 2015	
34	Private company	PV applications and systems	19 March 2015	
35	DOE	PV cells and modules	19 March 2015 18 June 2015	
36	SDO	General	25 March 2015	Via phone
37	NIST	PV cells and modules	26 March 2015	
38	University	PV cells and modules	6 April 2015	Via e-mail
39	Industry association	PV applications and systems	13 April 2015	
40	NREL	General	16 April 2015	
41	NIST	PV cells and modules	24 April 2015	
42	DOE	General	24 April 2015	
43	DOE	General	1 May 2015	
44	University		14 June 2015	
45	SDO	PV applications and systems	15 June 2015	
46	Private company (past)	PV cells and modules	16 June 2015	
47	NASA (past)	PV cells and modules	17 June 2015	
48	Private company	PV cells and modules	17 June 2015	