



## The role of the quality infrastructure within socio-technical transformations: A European perspective

Knut Blind

Fraunhofer Institute for Systems and Innovation Research ISI & TU Berlin, Chair of Innovation Economics, Sekr. H47, Straße des 17. Juni 135, 10623 Berlin, Germany

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### ABSTRACT

The role of quality infrastructure, i.e., regulation, standardization, metrology, conformity assessment, and accreditation, is analyzed in the general context of socio-technical transformations. Six policy intervention points structure their potential contributions. First, insights from the literature and anecdotal evidence reveal that regulation plays an essential role in niche stimulation, yet standardization is becoming more important for niche acceleration. However, regulation is essential for destabilizing the whole regime but also for addressing possible repercussions. Within the coordination of multi-regime interactions, the consistency of regulations and the interfaces to the other elements of quality infrastructure has to be assured. To tilt the whole landscape, the regulatory framework conditions have to be altered, allowing changes in the directionality of socio-technical systems. Finally, international standards can leverage nationally focused changes of regulations towards the global level. Policy recommendations and limitations conclude the paper.

### 1. Introduction

Energy provision, water supply, and transportation can be considered as socio-technical systems (Markard et al., 2012). They consist of individuals, firms, and other organizations, collective actors and their networks, but also of societal norms, regulations, technical and management system standards as institutions, as well as of material objects and knowledge (Geels, 2004; Markard, 2011; Weber, 2003).

Previous research on socio-technical systems has focused mainly on actors and the role of institutions in general. Following the Porter Hypotheses (Porter and Van der Linde, 1995), several studies have investigated the impact of, in particular, environmental regulations on innovation (see the review by Ambec et al., 2013). Meanwhile, the relevance of regulations for innovation in various areas has been acknowledged (see recent overview in McEntagart et al., 2020), and Edler et al. (2021) perceive regulation as a context factor within system dimensions and as drivers but also as barrier within transformations as

raised by Soininen et al. (2021). Earlier, Rogge and Reichert (2016) saw regulation as an important primary instrument type that addresses technology push with intellectual property rights, demand pull with performance requirements or even prohibitions, and liability law at the systemic level. In contrast, the explicit role of standards for innovation has only in the last decades been moved in the focus of research (e.g., Blind, 2016b) and also of policy, e.g., within the European Commission's standardization strategy (European Commission, 2022). Here, the objective is to leverage the European standardization system to contribute to both the green and digital transformations. It even states, "EU's ambitions towards a climate neutral, resilient and circular economy cannot be delivered without European standards on testing methods, management systems or interoperability solutions." (European Commission, 2022, p. 1).

Approaches to disentangle the different impacts of regulation and standards on innovation have only recently been investigated (Blind et al., 2017), but not for the whole transformation of socio-technical

E-mail address: [knut.blind@isi.fraunhofer.de](mailto:knut.blind@isi.fraunhofer.de).

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systems. Finally, analyses of the comprehensive impact of quality infrastructure<sup>1</sup>, i.e., regulation, standardization, metrology, certification, accreditation, and market surveillance, on the transformation<sup>2</sup> of socio-technical systems are - despite first attempts (Gonçalves and Peuckert, 2012) - still missing (Blind, 2015). However, recently the quality infrastructure has been the focus of a strategy paper by the British Department of Business, Energy & Industrial Strategy (BEIS et al., 2021), followed by a study on its role for selected emerging technologies (Brown et al., 2022). Furthermore, it has been explicitly mentioned as an important element for successful transitions of Germany's innovation system (OECD, 2022) in general and in particular for the development of the hydrogen economy in the German national strategy (German Federal Ministry for Economic Affairs and Energy, 2020), but also addressed in the context of the data economy (Puhl et al., 2021). Finally, Aswal (2020) highlights the role of the quality infrastructure for inclusive growth in India, whereas Marian et al. (2022) focus on its role, in general, but highlight the relevance of international standards and certification schemes for the development of solar plants in India.

Based on this background, we derive the following research question:

- What is the role of regulations and standards and the other elements of the quality infrastructure for the transformation of socio-technical systems?

The remainder of the paper is structured as follows. First, we provide an overview of the possible links between the elements of the quality infrastructure, in particular regulations and standards, on the one hand, and the transformation of socio-technical systems on the other. In addition, there are few studies addressing the role of certification or accreditation in this context, and only a single one is related to metrology. Based on these insights, we position the elements of quality infrastructure in the heuristic model of socio-technological transformations within the multi-level perspective (Geels, 2002), following the structure of six policy intervention points by Kanger et al. (2020). Finally, the paper concludes with several policy implications but also limitations pointing to proposals for future empirical research of transformations of specific socio-technical systems.

## 2. Literature on quality infrastructure relevant for socio-technical transformations

The literature review relies on reviews on the impacts of regulations (Blind, 2016a; McEntaggart et al., 2020) and standards (Blind, 2016b, 2022) on innovation. However, it is expanded by also considering the other elements of the quality infrastructure, i.e., metrology, certification, accreditation, and the quality infrastructure as a whole.<sup>3</sup>

<sup>1</sup> UNIDO (2018) defines quality infrastructure as: "the system comprising the organizations (public and private) together with the policies, relevant legal and regulatory framework, and practices needed to support and enhance the quality, safety and environmental soundness of goods, services, and processes. The quality infrastructure is required for the effective operation of domestic markets, and its international recognition is important to enable access to foreign markets. It is a critical element in promoting and sustaining economic development and environmental and social well-being. It relies on metrology, standardization, accreditation, conformity assessment, and market surveillance".

<sup>2</sup> The terms "transformation" and "transition" are often used synonymously. According to Hansmeier et al. (2022), (p. 1) "they describe comprehensive approaches to identify and implement (radical) non-linear paths and solutions for an intended substantial system change of both the environment and society." Since the term "transitions" is mainly used in sustainability research, following Hansmeier et al. (2022) we use "transformation", because it is established in more literature strands.

<sup>3</sup> Market surveillance as a just recently (e.g., by UNIDO, 2018) added dimension to quality infrastructure does not appear separately in the literature and is, therefore, subsumed under the enforcement of regulations.

### 2.1. Regulations

In general, we follow the first part of the very broad definition of regulations released by the OECD (e.g., OECD, 2021), which says that "regulation includes all laws, formal and informal orders, subordinate rules, administrative formalities, and rules issued by non-governmental or self-regulatory bodies to whom governments have delegated regulatory power." However, since we want to elaborate on the differences between regulation and standardization, we consider the second part of the definition as part of standardization, at least those documents released by the formal national, European, or international standardization bodies, because they have in any case formal agreements with the national governments, the European Commission or the United Nations.

Markard et al. (2012) and Gaziulusoy and Brezet (2015) highlight that socio-technical transformations also include modifications in regulatory institutions in addition to technological change. Furthermore, Köhler et al. (2019) argued that public policy, due to market failures related to transformations, can play a key role in influencing the directionality of transformations via regulation. Finally, Kanger et al. (2021) highlight that for deep transformations, the development of policy instruments, which create strong regulatory pressure on socio-technical systems, is recommended.

Scott (1995) distinguishes under the heading "regulative rules" between regulations, standards, and laws. In particular, companies are the focus of regulatory push and pull mechanisms (Dunphy et al., 2007; Greenstone, 2003). Within the structuration theory, Giddens (1984) highlights that actors, including companies, are embedded in rule structures, not only as passive rule-followers but also as users and eventually makers, e.g., by lobbying for favorable regulations. Therefore, rules are not just constraining but also enabling by increasing predictability, trust, and reliability. Here, it has to be noted that the constraining function is much more relevant on the level of socio-technical regimes<sup>4</sup>, but not for niches.<sup>5</sup> However, when niche innovations turn into regimes, the rules become more stable, constraining, and less enabling. Complementary to the role of rules in socio-technical transformations, Kivimaa et al. (2021) identified regulations, policies, and formal institutions as one of four dimensions where disruptions can be realized in transformations beyond technological disruptions (Johnstone and Kivimaa, 2018; Johnstone et al., 2020) as the introduction already pointed to the Porter Hypothesis (Porter and Van der Linde, 1995). Based on their review of 21 articles, regulations, but also their removal (Matschoss and Heiskanen, 2018) can be described as drivers of disruptive innovations (Enker and Morrison, 2017). Or they disrupt current socio-technical regimes (Kivimaa and Kern, 2016), e.g., stopping energy production in nuclear power plants (Hermwille, 2016) or from fossil fuels (Rosenbloom, 2019). In transition studies, destabilization has been conceptualized as a de-institutionalization process where sector-specific institutions, like regulations, are removed (Turnheim and Geels, 2013). In addition, it is argued that regulation can support disruptive innovations by fostering customers with a strong demand for environmental protection or energy efficiency (Ashford and Hall, 2018).

However, the effectiveness of regulations as drivers for

<sup>4</sup> Geels (2011, p. 27) defines socio-technical regimes "as semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of socio-technical systems." Regulations belong definitively to these regimes, whereas standards might change their character over time starting to be developed in niches and eventually referenced in governmental regulations and, therefore, becoming part of the socio-technical regime, like some certification schemes being mandatory for the providers of technical infrastructure.

<sup>5</sup> Following Kemp et al. (1998), according to Geels (2011, p. 27), "Niches as 'protected spaces' such as R&D laboratories, subsidized demonstration projects, or small market niches where users have special demands and are willing to support emerging innovations."

transformations in socio-technical regimes can be limited by different factors, e.g., fragmented government institutions, complex procedural rules, and substantive rules, like property rights allowing the exploitation of natural resources (Soininen et al., 2021). In addition, the impact of new regulations is less disruptive if they complement rather than replace existing regulations (Kern et al., 2017). Bauknecht et al. (2020) identify the tension between a regulatory focus on cost efficiency and the objective of transformative change as a further challenge. Brouillat and Maider (2020) highlight that the most severe regulations with rigorous enforcement and shortest timing do not necessarily lead to the envisioned outcome because they may put too much pressure on innovative firms. Therefore, they recommend that severe regulations be combined with a more flexible enforcement to secure sufficient competition and provide pioneering companies with enough time to develop solutions. From another perspective, if regulators are keen to apply their regulation strictly and are willing to accept a higher market concentration, they should reduce their stringency to enhance the prospects of transformation. This argument is in line with Rhodes et al. (2021), who show that flexible regulations can be a relatively cost-effective but also broadly accepted tool to achieve environmental objectives if they are well-designed. Still, interaction and equity impacts are also considered. Similarly, Bergquist et al. (2013) argue that regulation should rely solely on performance standards, including extended compliance periods, thus allowing firms flexibility to select and implement the appropriate compliance measures. Finally, according to Sareen and Haarstad (2021), regulators should be aware of the possible impacts the implementations of their regulations have because there are limited opportunities for regulations to be adapted (see, e.g., Geels et al., 2021).

In summary, regulation can contribute to innovation and, therefore, to the transformation of socio-technical systems, but may also be a barrier (e.g., Kemp et al., 1998 or Soininen et al., 2021) to their creativity, but also in the development and implementation of innovative solutions.

## 2.2. Standardization

In the literature on transforming socio-technical systems, the relevance of standards is mentioned mostly in the context of regulations, which have been elaborated above. However, the self-regulatory character of standardization and standards has, in general, not been highlighted, although Blind (2016b) provides a comprehensive review of the impacts of standards on innovation, but also on environmental objectives as illustrated by De Vries and Verhagen (2016) related to buildings' energy efficiency. Blind et al. (2017) show that the impact of regulations and standards on innovation itself is significantly different, which is even more important for answering our research question related to the transformation of socio-technical systems. Whereas in stable environments, regulation has fewer negative implications than standards on companies' innovation efficiency, standards are much more favorable in markets characterized by high technological uncertainty. They also play different roles in the multi-level perspective, i.e., regulations belong to the socio-technical regime, whereas standards are developed within technological niches. Sometimes, governments and supranational organizations, particularly the European Commission, mandate actors in the technological regimes and niches to develop standards to specify regulations and directives (e.g., Volpato, 2017).

Although standards can contribute to transformations in socio-technical regimes, only a few recent studies address this option in addition to governmental regulations. For the bioeconomy, Falcone and Imbert (2019) claim that standards can strengthen the current regulatory framework, whereas Gottinger et al. (2023) reveal its reciprocal relations and their links to scientific publications following the approach developed by Blind and Fenton (2022). Van der Vleuten (2019) points to the role of standards for deep transformations, like Europe's infrastructure transition in the food sector. However, in general, even comprehensive reviews, including proposals for future research agendas

(Köhler et al., 2019) or proposals for policy interventions for sustainability transitions (Kanger et al., 2020), still ignore this option.

Nevertheless, a few recent studies identify the role of standardization in transformation studies. For example, within their taxonomy of intermediaries promoting sustainability transitions, Kivimaa et al. (2019) characterize standardization bodies as niche intermediaries (see already Howells, 2006 on standardization bodies as intermediaries for innovation), developing a shared institutional infrastructure organizing knowledge flows between local experiments and the niches. Eventually, they produce and circulate even further knowledge via standards for the transformations of the socio-technical regime as a whole. This can also promote competition in transformations. For example, Li et al. (2016) highlight that standardizing technologies for electric vehicles can help reduce local protectionism in these markets.

Manning and Reinecke (2016) go one step further and elaborate on the role of transnational standardization within sustainability transitions of the global coffee sector because it can bring all relevant stakeholders across national borders together. In particular, they show how a modular governance architecture negotiated to integrate the interests of heterogeneous stakeholders which were developed in local niche experiments into a common international understanding of sustainability. Similarly, Losacker and Liefner (2020) argue within their concept of regional lead markets for environmental innovation that companies can drive national, but more importantly international diffusion processes via global standardization in order to gain a competitive advantage for their innovations.

Although the phenomenon of battles of standards has a long tradition (e.g., Shapiro and Varian, 1999), Reinecke et al. (2012) have only recently identified the multiplicity of sustainability standards, this could be solved by an approach called meta-standardization. However, this idea has not been further taken up. Instead, Fuenfschilling and Binz (2018) go beyond the implicit national focus in transition studies' socio-technical regime concepts and propose a 'global' regime perspective that includes the multi-scalar actor networks and institutional rationalities. These have an impact on transformation dynamics beyond national or regional borders. Due to missing international regulations, they point to the relevance of international non-governmental organizations, such as the International Organization for Standardization (ISO). They acknowledge global production networks and global value chains, which also rely on technology standards (see Blind et al., 2018 on the role of standards in European value chains). In addition, they point to transformations of infrastructure sectors (Markard et al., 2012), which are governed by international regulation not only through supranational treaties but also standards and certifications, i.e., technology and management system standards released by ISO and their related certification schemes. Overall, Fuenfschilling and Binz (2018) conclude that global regimes are most relevant in socio-technical systems, where dominant rationality is diffused based on international standards as scripts into national regimes. Taking a slightly different perspective, Iizuka and Ikeda (2021) exemplify the role of international standardization as an open platform that allows interactions among diverse stakeholders within healthcare robotics.

Following, Fuenfschilling and Binz (2018), but also Manning and Reinecke (2016), Mjörner and Binz (2021) identify an international standard, which has not been developed within a national or regional niche, but already on the global level. They consider standardization as an arena characterized both by institutionalization and re-scaling processes. The degree of institutionalization within global regimes increases with the existence of international standards reflecting, and thus reinforcing, institutional rationalities of regional and national regimes. Eventually, they conclude that standardization could be crucial for supporting the existing global regime and for constructing, diffusing, and institutionalizing 'new' (proto-) regime rationalities through the participation of actors active in niches in standardization processes. However, the investigated case study touches only on the margin of the relevance of the regulatory framework. Still, the interaction between

regulation and standardization has not been fully elaborated, such as in the global regime concept introduced by [Fuenfschilling and Binz \(2018\)](#). [Greenwood et al. \(2017\)](#) highlight that in supplier-driven markets, a ‘smart’ mix of mandatory regulations and voluntary standards needs a strong government in setting mandatory national regulations with voluntary standards best viewed as supplements. Still, a conceptual framework for the analysis of the interaction between regulation and standardization within transformations of socio-technical regimes is missing.

Besides the positive impacts of standards on innovation and the transformation of socio-technical systems, their negative implications for innovation also have to be mentioned, as summarized by [Blind \(2016b\)](#). In the context of studies on socio-technical transformations, [Tang et al. \(2020\)](#) and [Söderholm et al. \(2017\)](#) find modest or even insignificant impacts of institutional pressure via standards. Furthermore, [Kiefer et al. \(2019\)](#) and [García-Quevedo et al. \(2020\)](#) reveal that standards and certifications are barriers to transformations also due to high compliance costs; they might even act as obstacles to the exploration of systemic innovation, e.g., in agriculture ([Labarthe et al., 2021](#)), or radical innovations ([Clougherty and Grajek, 2023](#)).

In summary, the opportunities, but also the challenges of standardization and standards which can contribute to the transformation of socio-technical systems, have to be analyzed by taking their interfaces to the regulatory framework into account.

### 2.3. Metrology

Metrology has so far not – in contrast to standards – been linked with innovation studies in general and the analysis of transformations of socio-technical systems. For example, [King et al. \(2017\)](#) conclude that the relationships between metrology research, the use of measurement, and other components of the innovation system have still not been extensively researched. However, a significant share of standards is related to measurement, although only very few are focused on metrology in the narrower sense. [Swann \(2009\)](#) elaborated on the role of measurement for R&D and innovation. In particular, he highlighted its supporting function for process innovation. Finally, measurement can help to demonstrate product characteristics. Based on the analysis of case studies on metrology conducted by the U.S. National Institute of Standards and Technology NIST, [King et al. \(2017\)](#) find that increasing productivity, lowering transaction costs, and improving R&D efficiency are the impacts mentioned the most. Consequently, [Link \(2021\)](#) could reveal the productivity-enhancing impact of calibration tests as one output of measurement science or metrology on the aggregate productivity of the U.S. economy.

Recently, [Aswal \(2020\)](#) linked not only metrology but the whole quality infrastructure to the quadruple helix model of [Carayannis and Campbell \(2009\)](#), extending the well-established triple helix model of [Etzkowitz and Leydesdorff \(2000\)](#) dealing with the dynamics and evolution of the relations between universities, industries, and precision of measurements which can be traced back to the International Systems of Units, enables conformity assessment, i.e. calibration and testing, certification, and inspection. [Aswal \(2020\)](#) claims that quality infrastructure binds the four helices, namely government (1), university, science and technology institutions (2), civil society & media (3), and enterprises (4), that are responsible for the sustainable development of the economy and living standards. However, he does not elaborate on these links. Furthermore, the need for a robust quality infrastructure by various stakeholders in the implementation of regulations, economic growth, international trade, foreign direct investment, food safety, environmental protection, sustainable energy provision, affordable health, etc., is highlighted, but not further underpinned by empirical evidence.

Due to the significant overlap with standardization, metrology can also accompany the transformations of socio-technical systems and has, therefore, to be integrated into the conceptual approach.

### 2.4. Conformity assessment

Certification, as one of the most discussed elements within the literature in the context of quality infrastructure, is, in general, based on standards.<sup>6</sup> According to ISO (ISO/IEC 17000:2020), conformity assessment, as the demonstration that specified requirements (e.g., defined in standards or regulations) are fulfilled, includes activities such as testing, inspection, or certification. The presentation of its output can be either the form of a report or certificate, the form of a report or certificate; the latter, however, needs to involve an independent “third-party” attestation. Certification can be applied to products, management systems, or persons. The most prominent certification schemes discussed in the literature related to innovation, also due to their wide broad applicability (systems are often applicable independent of sector and company size) and data availability (e.g., annual ISO surveys) are the ISO management system standards related to quality, i.e., the ISO 9001 series, or environmental management (ISO 14001 series).

Without considering the framework of transformations of socio-technical systems, [Demirel and Kesidou \(2011\)](#) find that ISO 14001 certification effectively promotes end-of-pipeline technologies and research and development related to eco-innovations in the U.K. Still, this innovation - promoting impact - can also be observed based on a country panel ([Lim and Prakash, 2014](#)). [García-Quevedo et al. \(2020\)](#) reveal that environmental policies are driving the adoption of ISO 14001, and ISO 9001 because of their complementarity. Finally, in highly internationalized sectors, firms are more likely to adopt ISO 14001. This acts as further empirical evidence for the important role of not only international standards but also certification schemes within global socio-technical regimes ([Fuenfschilling and Binz, 2018](#)).

Further energy efficiency or information security system schemes are based on ISO or IEC (International Electrotechnical Commission) standards. Related to sustainability, there are private organizations, like the International Social and Environmental Accreditation and Labelling Alliance (ISEAL Alliance) ([Loconto and Fouilleux, 2014](#)), which also provide certification services based on their standards. In addition, however, there are numerous voluntary sustainability standards which can be linked to the 17 Sustainable Development Goals ([Bissinger et al., 2020](#)). Consequently, certification also plays a role in transforming socio-technical regimes, particularly related to sustainability.

However, the literature review reveals only a few studies explicitly highlighting the role of certifications in transforming socio-technical systems. As mentioned above, [Greenwood et al. \(2017\)](#) highlight the relevance of standards and related certifications in the transformation of the housing sector in England. [Siva et al. \(2017\)](#) pointed to a certification system implemented to support green building innovations in Singapore. [Enker and Morrison \(2017\)](#) also apply the socio-technical transition theory to the Australian building sector and identify building energy efficiency standards and related certification schemes as important approaches. In addition, [Binks et al. \(2020\)](#) highlight the importance of building standards to improve building services that enhance energy efficiency already in the design phase. Also related to the energy efficiency of buildings is smart metering. However, [Kochański et al. \(2020\)](#) reveal that missing or insufficient standards are inhibitors for the effective roll-out of smart meters in Europe.

In addition to the traditional building and energy sectors, standards, certification, and labels play an increasing role in the European bio-based economy ([Ladu and Blind, 2017](#)). Confirming [D’Adamo et al. \(2020\)](#) claiming that certifications must be used to inform consumers about bio-based products, [Morone et al. \(2021\)](#) revealed that the certification of bio-based products is indeed important for consumers’ purchase decisions.

Although certification schemes are, in general, based on standards,

<sup>6</sup> First-party (self-declaration) or second-party, e.g. by customers, conformity assessment are other options of conformity assessment.

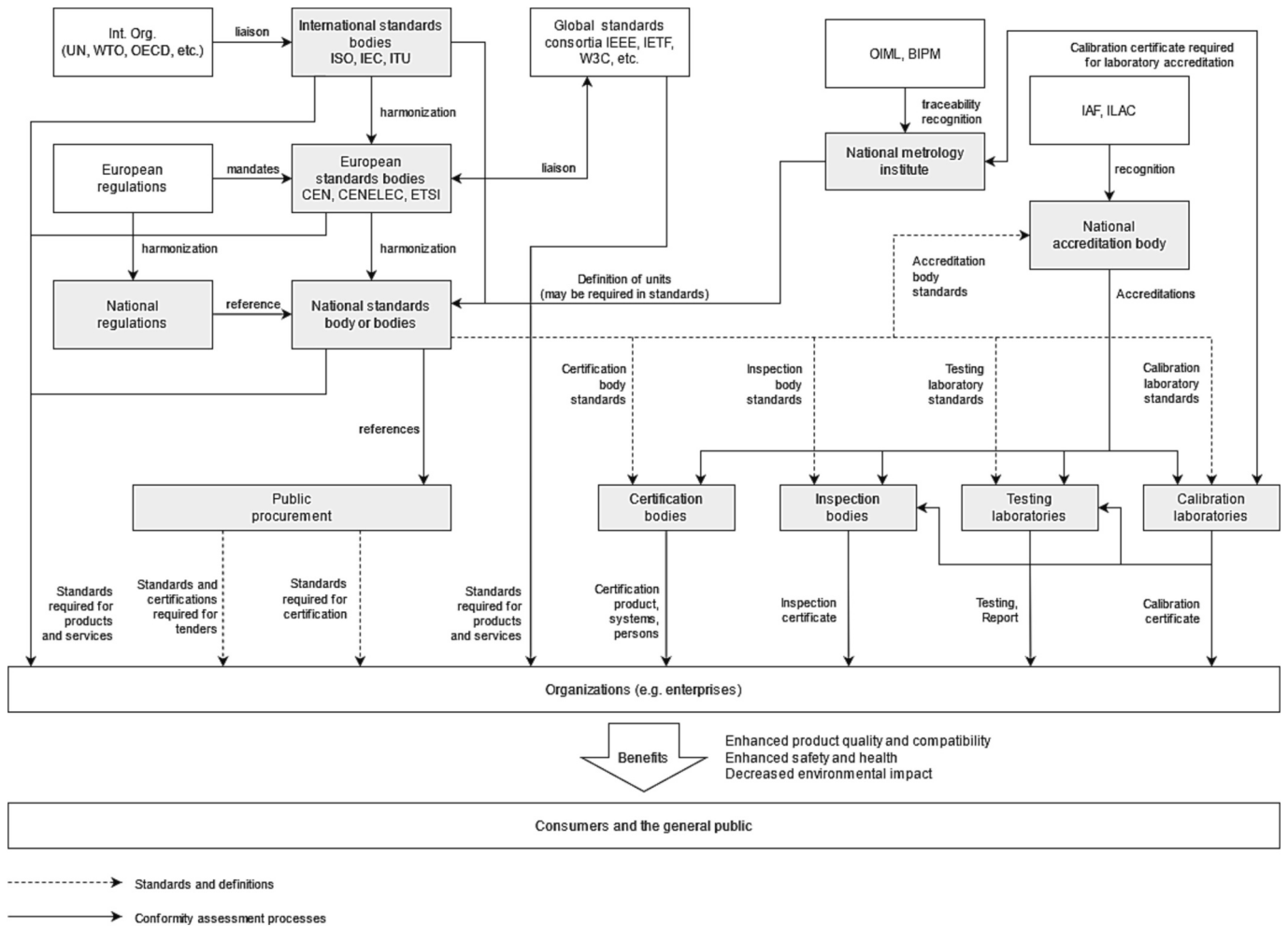


Fig. 1. The Quality Infrastructure from a European Union Perspective (Source: own development based on national quality infrastructure by Guasch et al., 2007).

they create an added value for socio-technical transitions, in particular, related to sustainability. Here, the certifications are based on international environmental management system standards or energy efficiency that are increasingly attractive for companies and other organizations as they signal, with higher credibility the implementation of their sustainability strategies. In addition, voluntary sustainability standards are developed beyond formal standardization bodies, like ISO, in numerous organizations, e.g., by ISEAL, which offer certification services. Finally, certifications are increasingly considered by regulators as proof of compliance with their technical regulations (Swann, 2010). Therefore, certifications can be regarded as boosters of the implementation of both standards and regulations.

2.5. Accreditation

Accreditation conveying the formal demonstration of the competence of conformity assessment bodies (ISO/IEC 17000), i.e., not only the layer above certification, but also the calibration, testing, and inspection bodies (e.g., Kellermann, 2019), has not yet been studied much in the context of innovation in general (e.g., stated by Frenz and Lambert, 2014). However, the limited research is not yet related to the transformation of socio-technical systems. Fouilleux and Loconto (2017) analyze the institutionalization of organic agriculture. The institutions shaping the area are a tripartite standards regime of governance (TSR) (Loconto and Busch, 2010). It links standard setting, certification, and accreditation via markets for services that are complementary to the market for certified organic products. At each of the three pillars of the

TSR, they analyze the development of the various markets and the role different actors played in the organic field. Since they conclude that the TSR is an effective heuristic approach to analyze contemporary global regulation, it makes sense to use the TSR to integrate these three elements of quality infrastructure into the further development of global socio-technical regimes introduced by Fuenfschilling and Binz (2018).

2.6. Overview of the quality infrastructure

Based on the presentation of the different elements of the quality infrastructure, we present in Fig. 1 an overview of the whole system from a European Union perspective, which has established a close link between regulations and directives and harmonized European standards. The interplay of the various elements will be elaborated further in the section about the coordination of multi-regime interactions.

3. The potential role of the quality infrastructure within socio-technical transformations

Based on the insights from the literature review about the role of the different components that make up the quality infrastructure, in particular regulation and standardization, in addition to concrete measures or initiatives within the different components of quality infrastructure, we start to integrate them into the multi-level perspective of transitions (Geels, 2002) of socio-technical systems (Geels, 2004). Since the quality infrastructure can be considered as an instrument or better infrastructure of public policy, we follow the six steps of policy

interventions introduced by Kanger et al. (2020). Another opportunity would have been to follow the Dialectic Issue Lifecycle Model (DILC) with its five phases (Penna and Geels, 2015), which is, however, less linked to policies and institutions and more actor-based (e.g. Bodenheimer and Dütschke, 2021). In principle, the life cycles' stages of technological innovation systems, i.e. formation, growth, maturity, and decline (Markard, 2020), could also help to structure our analysis of the different components' role the quality infrastructure has for the transformation of socio-technical systems, as already done by Swann (2000) related to standardization. However, the six policy intervention points by Kanger et al. (2020) turned out to be effectively linked to the different elements of the quality infrastructure, in particular the important coordination of multi-regime interactions.

### 3.1. Stimulation of different niches

Although the stimulation of various niches is suggested to initiate socio-technical transformations, it is also argued that emerging niche technologies have to become mature enough to create solutions that can eventually enter the market to support the further progress of socio-technical transformations.

In general, regulations can promote investments in research and development, often important preconditions for socio-technical transformations. Most important are the various regimes of intellectual property rights to incentivize companies or individual inventors (Carlin and Soskice, 2006), in particular patents (Thumm, 2023). The same applies to sector-specific regulations, like Orphan Drug Regulations (Gamba et al., 2021), that try to incentivize drug development focusing on rare diseases, which can be considered as rather narrow niches within a rather specific socio-technical transformation.

As mentioned above, Kivimaa et al. (2019) characterize standardization bodies as niche intermediaries, following Howells (2006) considering them as intermediaries for innovation in general. The different economic functions of standards supporting research and development elaborated by Blind and Gauch (2009) come into play in the early development of niches. In particular, common terminology standards are already relevant at the very beginning of new emerging science fields to facilitate communication between scientists. Then, measurement and testing standards, which are also closely related to progress in complementary metrology, can help to reduce transaction costs further in basic research. Since system innovations require the support of the whole socio-technical regime, standardization bodies can provide the platforms for all relevant stakeholders to exchange various, sometimes heterogeneous and conflicting ideas in order to eventually reach a consensus related to the directions of socio-technical transformations. Therefore, the comprehensive inclusion of all stakeholders is needed to increase the input legitimacy (Botzem and Dobusch, 2012) of the standardization process and ultimately the developed standards, which will help its successful implementation promoting successful socio-technical transformations. Since these basic standards have the characteristics of public goods (e.g., Kindleberger, 1983), public support might be needed because the industry as the main driver of standards development has insufficient incentives to initiate their development. Consequently, national governments, like Germany with a specific initiative or the European Commission within Horizon 2020 or Horizon Europe, have set up specific funding programs or have made efforts related to standardization, e.g. within the socio-technical transformation of the bioeconomy. They are eligible for funding within research programs to support standardization activities based on the results of research projects.

As mentioned above, metrology might become relevant for socio-technical transformations if progress in measurement and testing also needs new metrology standards. Then, the European Metrology Program for Innovation and Research (EMPIR) under Horizon 2020 or the following European Partnership on Metrology (EMP) under Horizon Europe might come into play, particularly related to funding metrology

or measurement science related to regulation and standards underpinning public policies that address societal challenges.

Within the stimulation of niches, the development of standards has only just started and there is not yet a sound basis for setting up certification schemes and accreditation programs. Therefore, these two components are generally not yet relevant for the acceleration of niches. However, certification bodies may try to enter promising emerging future markets, e.g., for Artificial Intelligence, to contribute due to its character of a general purpose technology to socio-technical transformation across different sectors at early stages. This may lead to parallel developments of certification schemes, although standardization processes, e.g., at ISO, have still not generated the necessary standards. Accreditation bodies are only becoming active in this early phase if public policy mandates them to develop accreditation programs for emerging certification schemes that have significant implications for socio-technical transformations.

### 3.2. Acceleration of niches

To accelerate niches to promote socio-technical transformations, regulations can be used to address different actors depending on the type of innovation (Pavitt, 1984). For example, according to Greenwood et al. (2017), supplier-driven innovation requires a strong regulatory role of the state. In addition, regulatory initiatives become relevant if they are elements of broader science, technology and innovation policy initiatives, like the previous Lead Market Initiative<sup>7</sup>, whose success also depends on the regulatory advantage of a country or the European Union as a region. Therefore, on the one hand, regulatory initiatives can be implemented to protect the first incumbents in niches following the infant industry argument, but also to open the supply side for the market entry of new actors, like start-ups, to increase the knowledge bases within niches and eventually to promote socio-technical transformations. On the other hand, however, regulation can promote the competition between companies that are already active within the niches, but also between different niches following different technological trajectories, e.g., electric vehicles vs. hydrogen-fueled vehicles, to push the socio-technical transformation of mobility. Additionally, regulations can also focus on potential actors on the demand side, like buyers of electric cars. Here, subsidy schemes or preferential treatments, e.g., regarding parking slots, can help to strengthen the demand side and push the diffusion of new technologies and related innovations. However, safety regulations might also be helpful to increase customers' trust in the new technologies and innovations.

Standardization bodies can be considered as a type of innovation platform, which are important to accelerate the niches according to Kanger et al. (2020). They are, therefore, not only niche intermediaries as categorized by Kivimaa et al. (2019), but more general intermediaries for innovation as already suggested by Howells (2006). Following standardization activities related to terminology, testing and measuring approaches, are relevant for the fast diffusion of new technologies and innovations and, therefore, the acceleration of niches. Further economic effects of standards are relevant for socio-technical transformations in addition to their information providing function helping to reduce transaction costs between the supply and the demand side. Here, the following different economic functions of standards come into play. First, standards reduce the variety of technologies or formats, which might allow exploiting economies of scale via mass production, driving down costs and eventually prices and increasing the number of potential customers, who are contributing to market take-up and growth. In addition, common standards might generate critical masses in the new emerging markets by attracting new companies providing products and services based on or being complementary to the published standards

<sup>7</sup> <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0860:FIN:en:PDF>.

(Blind, 2016b).

Furthermore, interface or interoperability standards generate positive direct and indirect network externalities (Katz and Shapiro, 1994), which are characterized by exponential mechanisms driving the fast diffusion of new technologies and innovations being the base for socio-technical transformations. Finally, before market entry or at its very early stages, health, environmental, and safety standards can help reduce risks and increase trust in new technologies, promoting their acceptance and market uptake. These standards might also be used as specifications of more general regulations, as in the New Approach or the New Legislative Framework set up by the European Union. This was recently reaffirmed in its new standardization strategy (European Commission, 2022).

New metrology schemes, for which demand might already be identified in the first phase of niche stimulation, can eventually be launched in the acceleration phase to create trust among businesses and consumers (Swann, 2009). Furthermore, new areas, like e-mobility, also become relevant for metrology, e.g., related to the requirements for the charging infrastructure, an important element of socio-technical transformations.

Whereas in the first stage of stimulating niches, certification and accreditation are generally not yet relevant, their significance for socio-technical transformations increases with the acceleration of niches. At first, certification bodies can base the development of their new certification schemes on the now available standards. Then, complementary accreditation bodies can start to launch programs for accrediting certification bodies in these new fields.

### 3.3. Destabilization of the regimes

Parallel to the development of niches, the incumbent regime has to be destabilized to allow the niches to establish themselves. In this context, regulations can play an important role for socio-technical transformations by banning specific technologies and practices and giving up the protection of incumbents, e.g., by removing market entry barriers for new actors.

Whereas the role of regulations to destabilize regimes has been acknowledged in the literature (e.g., Kanger et al., 2020), and in practice. The relevance of withdrawing existing standards has not yet been explicitly considered in this context. However, in practice, we find, on the one hand, that existing standards are replaced by completely new ones. They may be incompatible with the follow-up standards, which indeed means destabilizing the old technological regime. However, this constellation is not often observed, an exceptional example are the Internet Protocol versions IPv4 vs. IPv6. On the other hand, we see much more often (in mobile communication standards as revealed by Baron et al., 2016) that an older version of a standard is substituted by a new but the most likely compatible version, e.g., from the previous 4G to the new 5G standard of mobile communication, which is not a destabilization of the regime.

In metrology, there have been a few radical changes of replacing existing measurement schemes with new approaches, for example in 2019 switching the International System of Units to the approach that all seven units are described by seven base units. For the future, it is also an objective of redefining the kilogram by the number of atoms in a nearly perfectly round, softball-sized sphere of silicon-28 atoms. Although these changes are radical for metrology, they are less relevant for the destabilization of whole socio-technical regimes. However, to promote digital transformation in the area of metrology, a coordinated European Metrology Cloud has been initiated, which tries to substitute analog structures and can be, therefore, characterized as an initiative to destabilize the current infrastructure to push socio-technical transformations. Here, conventional analog calibration certificates, to prove that a measuring instrument has been calibrated and how this has been done, will be substituted by digital calibration certificates released by the metrology institutes (Hackel et al., 2017).

Phenomena similar to the incremental evolution of standards can be found in certification schemes. For example, the international management system standards, e.g., ISO 9001 on quality or ISO 14001 on environmental standards, have been revised several times by changing underlying requirements or testing procedures, which are only incremental changes. However, the introduction of the European Foundation for Quality Management (EFQM) Excellence Model can be considered as an attempt to destabilize the regime of ISO 9001 as well as the EU Eco-Management and Audit Scheme (EMAS) challenging ISO 14001 (Pohle et al., 2018). Here, different institutions enter a kind of war of different standards (Shapiro and Varian, 1999), whose outcome can certainly contribute to destabilizing an existing regime and pushing socio-technical transformations.

### 3.4. Addressing the broader repercussions of regime destabilization

Following the regime's destabilization, different stakeholders can be significantly affected, which might require some compensation.

To allow a smoother transfer to a significantly different regulatory regime, the compliance period could be extended, or exceptions can be allowed for specific affected companies and other stakeholders. In Germany, incumbents, which had made heavy investments, such as in nuclear power plants or other infrastructures, have been compensated following the decision to stop nuclear energy production in order to push the socio-technical transformation of the energy system.

Although companies will not be compensated if a new industry standard has been released, we can observe both the coexistence of different generations of standards, like 4G and 5G, in case of mobile communication and transition periods until a new generation of the standard will be implemented, because at the end the implementation of a standard is – in contrast to a regulation – voluntary.

However, changes in the metrology regimes can significantly influence metrology institutes and test laboratories. In particular, the digitalization of metrology, like digital calibration certificates, might make some laboratories offering calibration superfluous. Here, compensation schemes might need to be implemented, e.g., providing further training of staff employed in the predecessor institutions.

Similar to standards, we also observe both the coexistence of different editions of international management system standards, like ISO 9001 or ISO 14001, and transition periods from one generation to the next. These approaches allow companies to change the internal quality or environmental management smoothly. Optimizing the compliance costs helps companies to stay in the market and to contribute to socio-technical transformations.

The bodies responsible for accreditation could offer to extend the accreditation of the already accredited certification bodies when they have launched a new and probably more challenging accreditation scheme contributing to socio-technical transformations. Another option offered by the actors in the markets for certified goods and services would be to accept – at least for a transition period – certifications issued by non-accredited certification bodies.

### 3.5. Coordination of multi-regime interaction

Since the trajectories of socio-technical systems are developing not only endogenously, but are also influenced by external forces, e.g., other systems, they are, therefore, eventually the outcome of interdependent developments in various systems (Geels, 2005; Konrad et al., 2008; Schot and Kanger, 2018).

Concerning regulations, different coordination aspects have to be considered. In addition to cross-sectoral regulations, such as the General Product Safety Directive (2001/95/EC) in the European Union, there are many more sector-specific regulations. However, since socio-technical systems are increasingly rooted in different sectors, it is necessary to coordinate regulations across sectors to avoid inconsistencies or even contradictions. For example, there could be an interface between

**Table 1**  
Interrelations between the different elements of quality infrastructure.

Influence from.. ... to ...	Regulation	Standardization	Metrology	Conformity assessment	Accreditation
Regulation	Internal consistency /International coordination	Making regulation superfluous Allowing generic regulation (limited to “essential requirements”)	Approval relief (providing standardized measurements to fulfill legal requirements)	Approval relief (CE marking visible for market surveillance authorities)	Approval relief (ensuring consistent quality of Conformity Assessment (CA) results through competent CA bodies)
Standardization	In EU.: New Approach (ensuring wide applicability through the presumption of conformity and quality of standardization process using Harmonized Standards consultants)	Internal consistency/ International standards /allowing MRAs and MLAs	Need for standards	Need for standards (e. g., ISO/IEC 17000 series)	Need for standards (e.g., ISO/IEC 17000 series)
Metrology	Part of regulation in the regulated area	Base for metrology	Internal consistency/ international coordination	N/A	Accredited calibration bodies /allowing MRAs/MLAs
Conformity Assessment	Regulatory relief	Base for certification schemes	Consistent quality of CA results through standardized measurements	Internal consistency/ International certification schemes/ allowing MRAs/MLAs	Accredited certification bodies /allowing MRAs/ MLAs
Accreditation	Part of regulation, like GDPR or Cybersecurity Act	N/A	N/A	N/A	Internal/ International coordination (IAF)

regulations for the construction sector, and those for the energy sector, which might be related to energy efficiency of buildings and the common transformation of several socio-technical systems. Therefore, new regulations addressing the construction sector should consider improving energy efficiency. In addition, the [OECD \(2021\)](#) recently called for more international coordination, particularly in setting up regulatory framework conditions for new emerging markets complementing the approach of global socio-technical regimes by [Fuenfschilling and Binz \(2018\)](#). Here, the California effect ([Vogel, 1997](#)) and the Brussel effect ([Bradford, 2012](#)) have also to be mentioned. They focus on the export of originally national regulations, e.g., related to environmental regulations following the logic of the Porter Hypothesis, but also recently to the European General Data Protection Regulation (GDPR) ([Niebel, 2021](#)) being relevant for the transformation of the data economy.

In addition to the internal consistency of regulations, there is also – at least in some countries – a strong link to the body of standards. For example, South Korea implemented ISO/IEC 27018 for data protection in cloud computing as a national regulation ([Löhe and Blind, 2015](#)). In Germany, implementing an information security management system according to ISO/IEC 27001 is often obligatory for institutions running critical infrastructures ([Mirtsch et al., 2021](#)). The New Legislative Framework (NLF [https://ec.europa.eu/growth/single-market/goods/new-legislative-framework\\_en](https://ec.europa.eu/growth/single-market/goods/new-legislative-framework_en)) in the European Union New Approach foresees the division of work by the European Commission responsible for the more general directives and regulations, which are eventually specified by harmonized European standards. Sometimes, the European Commission launches mandates to the European standardization bodies to develop new harmonized European standards to complement already existing European directives or regulations related to socio-technical transformations, like the Green Deal. In some cases, standards might make the development of regulations unnecessary. There are different constellations of relationships between regulation and standardization, which require careful coordination to exploit their possible synergies to influence the development of different regimes efficiently, e.g., to promote the development of infrastructure for electric cars ([Wiegmann et al., 2017](#)).

Within standardization, different regimes might also have to be coordinated. In addition to checking the consistency of the stock of standards, standardization has been identified as a platform contributing to technology convergence ([Gauch and Blind, 2015](#)), which requires the coordination of the bodies of standards stemming from different socio-technical regimes.

Furthermore, metrology has to be coordinated with efforts on the regulatory side and with standardization. Here, interfaces have been implemented between the research program EMPIR or in the future between EMP and the standardization activities within the European standardization institutes.

Similarly, the consistency among certification schemes has to be assured, e.g., by common high-level audit approaches covering different certification schemes. Here, mutual or multilateral recognition agreements (MRAs/MLAs), which make multiple testing and certification efforts superfluous, can help push niches towards global socio-technical regimes, an aspect not considered by [Fuenfschilling and Binz \(2018\)](#).

In order to illustrate the recursive relationships between the different elements of the quality infrastructure, we summarize them in [Table 1](#).

### 3.6. Tilting the landscape

In its early stages, the multi-level perspective treated the landscape, which include demographical trends, political ideologies, societal values, and macroeconomic patterns ([Geels, 2011](#)), as exogenous shaping niches and the socio-technical regimes, e.g., in most of the transition paths presented by [Geels and Schot \(2007\)](#). However, the reciprocal relationship of socio-technical regimes influencing the landscape has recently been considered, e.g., by [Schot and Kanger \(2018\)](#) and [Kanger and Schot \(2019\)](#), but only analyzed in very few studies according to the review by [Kanger et al. \(2020\)](#). For example, [Imbert et al. \(2017\)](#) describe the case of landscape tilting in the area of bio-energy through strategic multi-level action combining EU and member states strategies. This kind of reciprocal influence can also be found in the concept of global socio-technical regimes by [Fuenfschilling and Binz \(2018\)](#), which can be considered part of the global landscape – at least from the perspective of national or regional socio-technical regimes. Here, international standardization is characterized by the broad participation of national stakeholders negotiating at the global level to achieve collectively binding arrangements, i.e., international standards. Eventually, they create more general framework conditions for changing the dynamics and directionality of socio-technical systems on the national level.

Regulations are certainly an effective instrument which contribute to tilting the landscape. In particular, for phasing out existing technologies, like fluorescent light bulbs, coal-based energy production, or nuclear power plants, rigorous changes in the regulatory frameworks are necessary. However, due to missing international regulations, negotiations and coordination are necessary to use the regulatory framework

**Table 2**

The relevance of the elements of quality infrastructure for different policy interventions points to trigger socio-technical transformations.

Intervention point	Regulation	Standardization	Metrology	Conformity assessment	Accreditation
Stimulation of different niches	IPRs (patents) Regulations related to R&D incentives (Orphan drugs)	Promote the development of standards supporting terminology and measurement and testing (e.g., via programs, like Horizon 2020)	Promote the development of metrology standards (e.g., via programs like European Metrology Program for Innovation and Research (EMPIR))	Not relevant	Not relevant
Acceleration of the niches	Demand subsidies, e.g., electric vehicles	Standards allowing the exploitation of economies of scale and reducing transaction costs Use standards to create trust among consumers/customers and increase network effects	Use new metrology approaches to create trust among consumers/customers	Use certification and labels to foster trust among consumers /customers Broaden the scope of existing certification schemes to de-limit to existing technologies	Use accreditation to foster trust among consumers/ customers
Destabilization of the regimes	Giving up existing regulations, e.g., protecting incumbents	Promote the application of new standards to substitute the application of existing standards	Replace existing measurement systems with new systems Digital Calibration Certification	Adjust existing certification schemes, e.g., by changing underlying requirements or testing procedures	Accredit new certification bodies and deny accreditation for incumbent certification bodies (e.g., by restricting certification to notified bodies like in the EU)
Addressing the broader repercussions of regime destabilization	Compensate incumbents for disadvantages created by new regulations Expand compliance period related to new regulations	Allow the coexistence of standards Expand transition period to a new generation of standards (e.g., mobile communication)	Compensate calibration bodies which are affected by changes of regulations	Allow the coexistence of certification schemes. Expand the validity period of expiring certification schemes	Prolong accreditation for incumbent certification bodies Accept certifications from non-accredited certification bodies Compensate closed accreditation bodies following EU regulation Align regulations with accreditation Avoid multiple testing costs by relying on mutual or multilateral recognition agreements (MRAs/MLAs)
Coordination of multi- regime interaction	Coordinate regulations across sectors (e.g., construction and energy sector) Use international standards as regulations Use standards to specify regulations	Check the consistency of stock of standards Use standardization to promote technology convergence Coordinate standards with regulations (NLF), including using standards as regulations	Coordinate regulations, but also standardization (CEN CENELEC Working Group Standardization Innovation and Research vs. EMPIR) with metrology	Check consistency among certification schemes Coordinate standards and certification schemes (ISO 9001, ISO 14001 editions) via common high-level structure and joint audits Use certificates to relieve regulatory burden	
Tilting the landscape	Alter the regulatory framework conditions enabling change in directionality of socio-technical systems	Alignment of international standardization along SDGs, in particular, climate change European (technological sovereignty) and national standardization strategies Standardization roadmaps	Digitalization of metrology	Conformity assessment schemes related to SDGs	Not relevant

effectively to promote innovation (OECD, 2021) and eventually to push transformations of socio-technical systems on the national and regional levels.

In contrast, international standards can be developed from the beginning within the international standardization bodies, as revealed by Fuenfschilling and Binz (2018), allowing their timely parallel implementation in companies and other organizations on the national level, in particular in latecomer countries (Choi et al., 2014). However, it has to be noted that the implementation of standards is in general voluntary in contrast to the obligatory regulations. However, with putting all standards at ISO and other organizations, like IEC and ITU (International Telecommunication Union), into the context of the SDGs (ISO, 2018), international standardization contributes to tilting the landscape which eventually influences the socio-technical transformations on a global level. This reorientation has been recently confirmed when the challenges of climate change were addressed by ISO standards in 2021 in the so-called London Declaration (ISO, 2021). In addition to the reorientation of the international standardization bodies towards sustainability, other informal standardization organizations have been developed in sustainability-related areas, like ISEAL as discussed above. Consequently, they have developed numerous voluntary sustainability standards (Bissinger et al., 2020). Other examples of national attempts to tilt the landscape related to standardization are

China's standardization project 2035 (e.g., Seaman, (2020), or Rühlig, (2020)) or the recently published European standardization strategy (European Commission, 2022) addressing Europe's twin green and digital transformation, but also to secure European values. Further activities within standardization bodies are the development of roadmaps for emerging technologies, like Artificial Intelligence (AI) or the Circular Economy, which aim to use standards to tilt existing landscapes, e.g. ethical concerns regarding AI.

The revision of International Systems of Units in 2018 is certainly a significant change within metrology, which has no immediate implications on socio-technical transformations in contrast to the institutional changes of privatizing originally public metrology institutes. However, the progressing digitalization has started in several niches and is now changing the socio-technical regimes and potentially also the landscape in metrology. Therefore, the already started and further progressing digitalization of the whole national, European, and even global metrology system can tilt the metrology landscape by allowing global approaches challenging national infrastructures, having eventually implications on specific socio-technical regimes and niches.

Regarding conformity assessment and specifically certification we can observe only phenomena which are eventually based on the changes in the direction of standardization, e.g., towards the Sustainable Development Goals (SDGs), and the eventually published standards, that

are the basis for certifications schemes (e.g., Bissinger et al., 2020). In addition to some institutional changes of certification bodies, e.g., the disentangling of standardization and certification into two institutions in Spain, which has only limited implications for tilting landscapes, two phenomena already mentioned have to be reiterated. First, governments take international standards and implement them as national regulations, which increases the international and reduces the national influence in setting rules. Second, successful certification can already be a requirement for companies' market access, e.g., to critical infrastructures. Finally, such certifications can lead to a "regulatory relief" for companies, i.e., fewer costly compliance efforts related to regulations (Swann, 2010). These opportunities must be seen in close connection to using regulations to tilt existing landscapes.

### 3.7. Summary

The following Table 2 summarizes what has been derived when analyzing the relevance of the different elements of quality infrastructure for the different intervention points within the framework of socio-technical systems' multi-level perspective.

The findings of attributing the different components of the quality infrastructure to the six steps of policy interventions are summarized in a comprehensive matrix. Overall, we confirm the important role of radical regulations following the tradition of the Porter Hypothesis for the stimulation of different niches. Moreover, since research and development are important for the emergence of niches, the effective interfaces to standardization, including metrology (Blind and Gauch, 2009), have to be assured at least for public-funded research and innovation programs, like Horizon Europe, as highlighted in the standardization strategy published by the European Commission (2022).

Based on the output of standardization processes, the acceleration of niches can be promoted by exploiting the various economic functions of standards, e.g., economies of scale and network effects. Here, certification schemes by accredited conformity assessment bodies can play a supporting and enhancing role.

The destabilization of the regime certainly requires significant changes to the regulatory framework. In standardization substituting existing standards by incompatible follow-up solutions has taken place on very few occasions, e.g., standards' battles. The same applies to conformity assessment and accreditation. However, we have seen some significant changes in the metrology system, yet only a few, like its digitalization, which might be able to destabilize the whole regime.

Since the destabilization of regimes often has broader repercussions, policymakers have to address them by changing the regulatory framework or launching other public policies, e.g., financial support for those organizations heavily affected. Standardization and the other elements of quality infrastructure might be less effective for addressing these very different repercussions due to limited instruments, lack of incentives and responsibility of the involved stakeholders, i.e., above all industry.

Since regimes are not isolated, but interact with other regimes, their interactions must be coordinated to facilitate socio-technical transformations. It is not only necessary to coordinate national regulations across sectors, e.g., between the construction and the energy sector to increase energy efficiency, but also at the international level, as recently pointed out by the OECD (2021), to address global challenges. Since there are in general no international regulations, but international standards in many areas, the latter can play an important role in transforming global socio-technical regimes (Fuenfschilling and Binz, 2018). It is important to mention that international standards do not have to be developed in national or regional niches and then transferred to the international level as the next step. They can even develop at the international level and then be implemented at the national level (see, for example, Miörner and Binz, 2021). Furthermore, it has to be taken into account that standards can also be used to specify the technical details of the more general regulations, which require the coordination of another interface. This is challenging indeed as recently reconfirmed

in the EU standardization strategy (European Commission, 2022). In addition, coordination within standardization is needed, similar to the alignment between different sector-specific regulations. This pressure will increase with the progressing convergence of technologies (Gauch and Blind, 2015). Furthermore, the metrology system has to be aligned both with the regulatory framework and the stock of standards. Finally, the interfaces between different certification schemes, like the international quality or environmental management system standards and accreditation, have to be coordinated.

For tilting the landscape as the last policy intervention point, the regulatory framework conditions – if possible coordinated on the international level – have to be altered to enable the change in the directionality of socio-technical systems, e.g., to address the challenges of climate change. Regarding standardization, such tilting of the landscape has been tried by aligning the international standardization activities towards the objectives of SDGs. It has just recently put climate change into the focus. However, Blind and Heß (2023) reveal that standardization is – based on the assessment of the stakeholders – still most closely linked to the SDG 9 focusing on industry, innovation, and infrastructure; they have also revealed that the transition towards the SDGs and, therefore, the tilting of the landscape requires definitely several years more work on this component of the quality infrastructure. At the European, but also at the national level, the development and release of standardization strategies are indications for trying to put standardization into the equation, allowing the landscape to tilt towards the SDGs and address other geopolitical challenges, e.g., related to assuring technological sovereignty. Following the tilt of the landscape within standardization towards the SDGs reducing the relative importance of the economic function of standards, certification schemes accompanied by eco and energy labels followed this change towards sustainability, including the emergence of new standardization and conformity assessment bodies. In addition to the tilt of the landscape towards sustainability, the progressing digitalization has also reached the quality infrastructure and its components, e.g., in the digitalization of certification, accreditation, and metrology.

## 4. Conclusion

This paper has condensed findings from the literature on quality infrastructure and its components, particularly regulation and standardization. It has put them into the context of the conceptual framework of six policy intervention points related to sustainability transitions presented by Kanger et al. (2020).

We showed that the current literature on the elements of the quality infrastructure is focused on regulation and standardization, implicitly on innovation, but not explicitly on transforming socio-technical regimes, in particular, to trigger the stimulation and acceleration of niches. However, both the other elements of the quality infrastructure and the other policy intervention points have been neglected despite the crucial coordination of multi-regime interaction.

In addition, we have also revealed the close interaction between standards and regulation. Consequently, the relevance of coordinating multi regime interactions has been confirmed. However, this coordination has to be considered in relation to the different components of the quality infrastructure, at the latest for the acceleration of niches and not only after the destabilization of regimes.

Our approach leads us then to the derivation of policy implications related to the role of the different quality infrastructure components for the transformation of socio-technical systems structured along the policy intervention points introduced by Kanger et al. (2020). First, the stimulation of niches needs crucial interventions by regulation. Second, however, the regulator should exploit the potential of the capacities and incentives of the stakeholders involved in standardizing the complementary stimulation of niches. Third, the acceleration of niches, particularly across borders, can benefit from the properties of standards endorsed by conformity assessment and accreditation. Regulation is

generally more effective in destabilizing regimes than standardization, possibly accompanied by conformity assessment and accreditation. Similarly, repercussions of regime destabilization can mainly be addressed by the regulator, complemented by further public policies. However, the coordination of multi regime interactions requires the synchronization of rules within the regulatory framework and the body of standards as well as between themselves and metrology, conformity assessment, and accreditation. For tilting the landscape, again, the regulatory power of the government is an essential driver. However, significant shifts can also be achieved within standardization and metrology, followed by conformity assessment and accreditation. Although regulation is essential both for triggering the stimulation of niches and tilting the landscape, standardization and metrology accompanied by conformity assessment and accreditation can help accelerate the development of niches and the need to be integrated with the coordination of the multi regime interaction. In summary, the quality infrastructure in total and its single elements might play different roles in the various types of transformation pathways, e.g., purposive transitions vs. emergent transformations.

As a general challenge, we would call for a more theoretical reflection of the role of the quality infrastructure, its components, and their interactions with socio-technical transformation so that the empirical evidence could be coupled with analytical reasoning. For example, we did not consider the agency of the involved actors, i.e., that they build the institutions the quality infrastructure is based on driven by their interests and enabled by their means, which might lead to a delay in socio-technical transformations.

Nonetheless, it has revealed promising options for future research. However, further empirical work, including other sources and methodologies, such as interviews or surveys, remains to be done in order to analyze all elements of the quality infrastructure. This includes their possible negative implications for the transformation of different socio-technical regimes in other countries, in particular outside the European Union.

### CRedit authorship contribution statement

**Knut Blind:** Conceptualization, Methodology; **Knut Blind:** Writing-Original draft preparation. **Knut Blind:** Investigation. **Knut Blind:** Supervision; **Knut Blind:** Writing-Reviewing and Editing.

### Data availability

No data was used for the research described in the article.

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Knut Blind studied economics, political science, and psychology at Freiburg University. During his studies, he spent one year at Brock University (Canada), where he was awarded a BA. Finally, he earned his Diploma in Economics and later his doctoral degree at Freiburg University. Between 1996 and 2010, he joined the Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, Germany, as a senior researcher and, at last, as head of the Competence Center "Regulation and Innovation". In April 2006, Knut Blind was appointed Professor of Innovation Economics at the Faculty of Economics and Management at the Berlin University of Technology. Between 2008 and 2016, he also held the endowed chair of standardization at the Rotterdam School of Management of Erasmus University. From April 2010 to September 2019, he was linked to the Fraunhofer Institute of Open Communication Systems in Berlin. Since October 2019, he has been head of the business unit "Innovation and Regulation" at the Fraunhofer Institute for Systems and Innovation Research. In 2012, he initiated both the Berlin Innovation Panel and the German Standardization Panel followed by a pilot of a European Standardization Panel launched in 2023. Besides numerous articles on patents, he published several contributions on standardization and further innovation aspects in refereed journals.