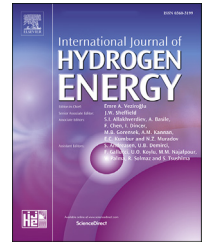


Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

ScienceDirect

journal homepage: [www.elsevier.com/locate/he](http://www.elsevier.com/locate/he)

# Pathways to the hydrogen economy: A multidimensional analysis of the technological innovation systems of Germany and South Korea

Parsa Asna Ashari <sup>a,b,\*</sup>, Hyochan Oh <sup>c</sup>, Claudia Koch <sup>a</sup>

<sup>a</sup> Bundesanstalt für Materialforschung und -prüfung (BAM), Department S.2, Digitalization of Quality Infrastructure, Rudower Chaussee 11, 12489 Berlin, Germany

<sup>b</sup> Technische Universität Berlin, Chair of Innovation Economics, Straße des 17. Juni 135, 10623 Berlin, Germany

<sup>c</sup> H2KOREA, 4F, Royal Building, 34 Banpo-daero, Seocho-gu, Seoul, Republic of Korea

## HIGHLIGHTS

- We comparatively analyze the hydrogen economies of Germany and South Korea.
- We assess the technological innovation systems (TISs) from multiple perspectives.
- We identify the industrial, political, and social determinants of the hydrogen economy.
- Results highlight more advancements in the South Korean hydrogen economy.
- We derive implications for advancing the hydrogen economies of both countries.

## ARTICLE INFO

### Article history:

Received 9 June 2023

Received in revised form

11 August 2023

Accepted 24 August 2023

Available online 14 September 2023

### Keywords:

Hydrogen economy

Technological innovation system

Quality infrastructure

Multidimensional technology

adoption

Social acceptance

## ABSTRACT

The global trend towards decarbonization and the demand for energy security have put hydrogen energy into the spotlight of industry, politics, and societies. Numerous governments worldwide are adopting policies and strategies to facilitate the transition towards hydrogen-based economies. To assess the determinants of such transition, this study presents a comparative analysis of the technological innovation systems (TISs) for hydrogen technologies in Germany and South Korea, both recognized as global front-runners in advancing and implementing hydrogen-based solutions. By providing a multi-dimensional assessment of pathways to the hydrogen economy, our analysis introduces two novel and crucial elements to the TIS analysis: (i) We integrate the concept of ‘quality infrastructure’ given the relevance of safety and quality assurance for technology adoption and social acceptance, and (ii) we emphasize the social perspective within the hydrogen TIS. To this end, we conducted 24 semi-structured expert interviews, applying qualitative open coding to analyze the data. Our results indicate that the hydrogen TISs in both countries have undergone significant developments across various dimensions. However, several barriers still hinder the further realization of a hydrogen economy. Based on our findings, we propose policy implications that can facilitate informed policy decisions for a successful hydrogen transition.

© 2023 The Authors. Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

\* Corresponding author. Bundesanstalt für Materialforschung und -prüfung (BAM), Department S.2, Digitalization of Quality Infrastructure, Rudower Chaussee 11, 12489 Berlin, Germany.

E-mail addresses: [Parsa.Asna-Ashari@bam.de](mailto:Parsa.Asna-Ashari@bam.de) (P. Asna Ashari), [hcoh0208@h2korea.or.kr](mailto:hcoh0208@h2korea.or.kr) (H. Oh), [Claudia.Koch@bam.de](mailto:Claudia.Koch@bam.de) (C. Koch).

<https://doi.org/10.1016/j.ijhydene.2023.08.286>

0360-3199/© 2023 The Authors. Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Hydrogen is a versatile energy carrier with many potential applications, including hard-to-abate industrial processes, mobility, energy storage, heating, and power supply. Coupled with its potential to decarbonize the energy system, provided that ‘green’ hydrogen produced from renewable energy sources is used, and to ensure future clean energy security, hydrogen is expected to play a pivotal role in the ongoing energy transition towards net-zero emissions [1–3].

This potential has brought hydrogen into the spotlight of industry, politics, and societies, with numerous countries worldwide adopting national hydrogen policies and strategies, which outline pathways to the hydrogen economy [4–7]. Among them, Germany and South Korea assess hydrogen technologies as essential for the future viability of their economies [8,9]. Committed to the 2015 Paris Agreement [10], both countries expect hydrogen to contribute to achieving greenhouse gas reduction goals [11]. This commitment is reflected in massive investments in hydrogen technologies [12,13], which have led both countries into global leaders in hydrogen research and innovation [6]. However, in their transition, both countries differ regarding the objectives and target sectors, value chain specialization, and market size of their hydrogen economies. Furthermore, different economic, political, and social factors have shaped the hydrogen economies of these two countries to different degrees.

In sustainability transition pathways, previous research emphasizes the importance of involving all relevant stakeholder perspectives to comprehensively understand the evolution of niches toward increased technology adoption [14–16], including the hydrogen transition. While previous studies have provided multidimensional stakeholder analyses related to the hydrogen economy, they consider stakeholder categories that have already substantially shaped the hydrogen economy but not those that could become relevant in the future, such as in the exclusive analysis of the members of the *Danish hydrogen and fuel cell network* [17,18]. Moreover, these studies are geographically limited to single countries [17–21], do not capture recent developments following the adoption of numerous hydrogen strategies [21,22], or focus on stakeholder communication strategies to increase social acceptance rather than analyzing hydrogen technology adoption multidimensionally [23].

Therefore, the significance of this study lies in synthesizing relevant perspectives from industrial, political, and social stakeholders in two distinct countries towards the hydrogen transition by identifying the key drivers and barriers and deriving accordant policy implications.

To this end, this study comparatively analyzes the hydrogen *technological innovation systems* (TIS) in Germany and South Korea. Previous research has investigated the hydrogen TIS from various perspectives. However, we identify several research gaps: 1.) Most studies consider only one specific sector or hydrogen application [24–26] and only one single country or region [24,26–29]; 2.) At the theoretical level, no study applies the TIS life-cycle approach following Markard [30] to comparatively analyze the development stage of the hydrogen TISs in two countries; 3.) Previous hydrogen TIS

research has largely neglected the social perspective despite its importance for TIS development, i.e., the active and passive acceptance of hydrogen technologies in the general public.

Our multidimensional stakeholder analysis addresses these research gaps at multiple levels: First, we provide a qualitative analysis of two countries that are expected to become central players in a global hydrogen economy, which is, to the best of our knowledge, the first to apply the TIS life-cycle framework. Herewith, we address the spatial dimension of a TIS analysis beyond national boundaries [31,32]. Second, we cover major stakeholder categories relevant to the development of the hydrogen TIS, specifically addressing the social acceptance of hydrogen technologies and highlighting the role of ‘quality infrastructure’ (QI) as a means of safety and quality assurance. Third, we derive meaningful policy implications regarding the determinants of a successful hydrogen transition. The following research questions specify our research objectives:

**RQ1.** What are the drivers and barriers to hydrogen TIS development in Germany and South Korea from the industrial, political, and social perspectives?

**RQ2.** How do Germany and South Korea differ in terms of their TIS development phase?

**RQ3.** What are the determinants of successful hydrogen TIS development?

To answer these questions, we conducted and analyzed 24 semi-structured expert interviews with German and South Korean stakeholders representing the industrial,<sup>1</sup> political, and social perspectives on hydrogen technology adoption and acceptance. The remainder of this paper is structured as follows: Section 2 presents the conceptual background, followed by an overview of the research methods and data in Section 3. Section 4 is a joint results and discussion section, followed by concluding remarks and policy implications in the final Section.

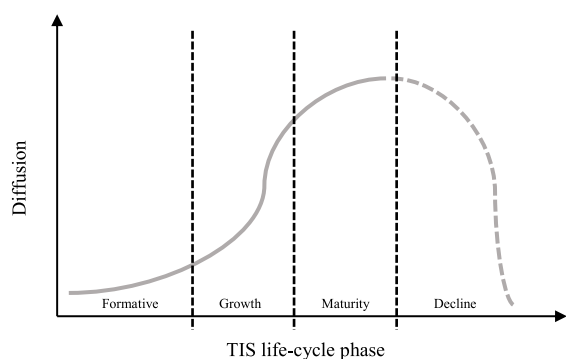
## 2. Conceptual background

### 2.1. Technological innovation systems (TIS) approach

The *technological innovation systems* (TIS) approach has been increasingly used to analyze emerging, clean technologies in the context of sustainability transitions [6,33–35]. A TIS consists of various dimensions, i.e., “technologies, actors, networks, and institutions, which actively contribute to the development of a particular technology field” [36]. Previous TIS research is divided into two major tracks: 1.) TIS analyses revolving around the seven system functions<sup>2</sup> [35,37]; and 2.)

<sup>1</sup> The selection of industry representatives reflects the whole hydrogen value chain, including various applications, and, thus, the sectoral TIS perspective [38].

<sup>2</sup> Following Bergek et al. [35]: Knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation, market formation, legitimation, resource mobilization, and development of positive externalities.



**Fig. 1 – Life cycle of the technological innovation system (based on Hekkert et al. [39] and Markard [30]).**

analyses of the structural TIS elements [30,36,40,41]. In the tradition of structural TIS concepts, the TIS life-cycle framework by Markard [30] assesses the development phases of a TIS. Markard [30] distinguishes four life-cycle phases: the formative, growth, mature, and decline phase (Fig. 1). The phases differ with respect to the maturity of the TIS dimensions, i.e., the size and actor base, the institutional structure and networks, technology performance and variation, and the TIS-context relations. With increased TIS growth, more actors enter the TIS, networks are formed, institutional structures and markets increasingly take shape, technology performance is optimized, variation is reduced, and the focal TIS increasingly impacts its technological, geographical, or sectoral context. This development prevails until the mature phase, when the TIS life cycle starts to stagnate, followed by a decline across all TIS dimensions in the final TIS life-cycle phase [30].

Previous research has largely neglected the TIS life-cycle framework in the analysis of the hydrogen TIS structures, except for Asna Ashari et al. [6], who applied it for their quantitative analysis of the global hydrogen TIS.

In the tradition of functional TIS analyses, Bach et al. [24] comparatively analyzed battery-electric and hydrogen solutions for maritime transport in Norway based on the qualitative analysis of 72 semi-structured interviews, finding that the TIS functions of hydrogen solutions are weak to intermediate. In their event history analysis of the UK fuel cell TIS between 1954 and 2012, Hacking et al. [27] find increasingly positive feedback loops between the fuel cell TIS functions and enhanced public-private R&D support. Furthermore, the authors highlight spatial differences within the UK regarding the fulfillment of TIS functions. Expanding the functional analysis of purely national TISs, Andreasen and Sovacool [34] compare the fuel cell TISs in Denmark and the USA based on the seven TIS functions and identify national differences. Köhler et al. [25] analyze the TIS functions of various sustainable road-vehicle technologies in the EU, including fuel-cell electric vehicles (FCEVs). The results demonstrate more mature TIS functions and higher commercialization of low-carbon vehicles other than FCEVs, such as electric vehicles.

Kushnir et al. [26] studied the deployment of hydrogen technologies in the Swedish steel industry by analyzing the TIS structures and functions qualitatively and literature-based, complemented by a quantitative publication and

patent analysis of the ‘knowledge development’ function. Similarly, the analysis of the European power-to-X TIS by Decourt [28] combines functional and structural TIS elements. The author highlights that the power-to-X TIS, with hydrogen as a substantial pillar, is increasingly growing but showing weaknesses in terms of market formation, conflicts in the actor base, and matters of social acceptance. Suurs et al. [42] analyzed the TIS functions and structures of the hydrogen and fuel cell TIS in the Netherlands between 1980 and 2007. The results point to the long evolution of TIS development but the yet limited TIS maturity. In their structural TIS analysis, Musiolik and Markard [29] investigated formal networks in Germany’s stationary fuel cell TIS based on interviewees’ motives to engage in networks and explore new technological fields, finding a complex and fragmented network structure of the German TIS that hampers overall TIS development.

Previous research contributes to a better understanding of the hydrogen TIS in various single countries, sectors, and applications. However, no TIS study covers the scope of all value chain activities, including the production, storage, transport, and use of hydrogen. Furthermore, we find no comparative analyses of two countries’ TIS life cycles and the social perspective within the TIS. Therefore, the work presented in this paper aims to address this research gap by comprehensively synthesizing the determinants of the hydrogen transition from multiple perspectives.

## 2.2. Quality infrastructure, safety, social acceptance

Previous research has highlighted the importance of social acceptance for the diffusion of hydrogen technologies, especially those in proximity to the general public, such as hydrogen refueling stations (HRSS) or FCEVs [43,44]. Since both Germany and South Korea target the mobility and power sectors with their hydrogen activities, among others, the proximity of these hydrogen applications to the general public can influence active and passive social acceptance, which can, in turn, affect TIS development.

Although Markard [30] describes “collective expectations, cognitive frames, user practices, social norms or culture” as part of the institutional structure of a TIS, empirical hydrogen TIS research considers the social perspective only marginally (e.g., Refs. [26,28]). Instead, the perspectives of selected industries and markets on the use of hydrogen energy [24–26], policies [24,34,42], and R&D [6,27] have been in focus. While safety and trust have largely been overlooked in previous TIS research, they are crucial to the sustained social acceptance and adoption of hydrogen technologies [6,58,104]. Therefore, we integrate a strong focus on safety into our TIS life-cycle approach, specifically to account for the crucial social perspective. To adequately address the link between safety and social acceptance, we refer to ‘quality infrastructure’ (QI), integrating it into the TIS framework. UNIDO defines QI 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” [45]. The QI consists of five elements, each contributing to the set objectives: standards and regulations containing requirements on products, processes, and

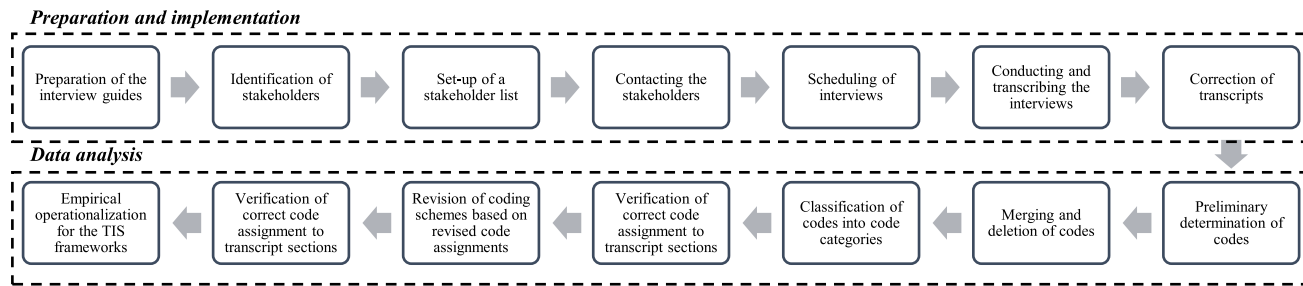


Fig. 2 – Overview of the research procedure.

services; conformity assessment; accreditation; market surveillance; and metrology [46,47]. QI contributes to the safety of products, processes, and services [47,48], and increases trust, transparency, and thus acceptance of technologies [46,49,50]. Given these features and objectives, QI closely relates to the institutional structure of a TIS, defined as “the degree of structuration of a TIS, including different kinds of institutions and their coherence and impact” [30]. Markard [30] proposes, among others, the regulatory and legal framework and standardization – thus core QI elements – as indicators of the institutional structure. Therefore, we integrate the QI and the associated social acceptance implications into the TIS’s institutional structure.

### 3. Research setting, data, and methods

The research setting of our analysis is the hydrogen TISs in Germany and South Korea, i.e., the TISs surrounding the use of hydrogen and all relevant technologies along the hydrogen value chain. In the global trend towards promoting hydrogen technologies and the development of hydrogen economies, both countries have been global frontrunners in hydrogen-related research and innovation [6,51] and have adopted national hydrogen strategies [4,5,52].

To comprehensively analyze their hydrogen economies following the structural TIS life-cycle framework [30], we deploy a qualitative, explorative research design. To this end, we conducted semi-structured expert interviews with relevant stakeholders to gain insights into the structural TIS dimensions. Semi-structured interviews bear the advantage of not adhering to a rigid, predefined interview structure but allow the interviewer to react to the interviewees’ responses with follow-up questions and to delve more deeply into specific topics [53].

Fig. 2 illustrates the research procedure in detail: First, we identified adequate stakeholders based on their influence in the hydrogen sector and relevance to our research objective following Bryson’s [54] power-interest grid. The stakeholders included experts on the domestic hydrogen economies, research and technology development, policies and regulations, safety aspects, and the social perception and acceptance of hydrogen technologies. We selected interviewees from three categories: 1.) private companies in the hydrogen sector, 2.) experts on the political and regulatory framework, and 3.) experts on social perception and acceptance. Subsequently, we contacted these stakeholders via email or phone.

This resulted in 11 interviews with German and 13 interviews with South Korean stakeholders, which we conducted between June and August 2022 (Table 1).<sup>3</sup>

We designed one interview guide for each stakeholder category with different thematic focuses relevant to our research objectives. The setting was face-to-face and online interviews conducted in German, Korean, or English, which typically lasted between 40 and 60 min. Following the initial transcription of the interviews using the transcription function of *Microsoft Teams* [55], we corrected erroneous transcript sections and coded the transcripts using the qualitative data analysis software *MAXQDA* [56]. As a coding technique, we applied open coding following Strauss and Corbin [57], defined as “the analytic process through which concepts are identified and their properties and dimensions are discovered in data” [57].

In contrast to structured coding with predefined code categories, open coding increases flexibility and reduces bias from a loss of information resulting from relevant transcript sections not fitting the predefined codes [57,58]. Facilitated by the design of interview guides and the selection of interviewees, we connected the codes identified from open coding with the TIS dimensions and QI instead of pre-structuring codes according to our framework.

The open-coding approach involved the following steps<sup>4</sup>: First, we created a preliminary set of codes from the interview transcripts, which we merged or deleted in the second step to compress the codes. Third, we organized each code into thematically ordered code categories for a more sophisticated classification. Fourth, we verified that each code was assigned to the appropriate transcript segments of the interviews. Upon revising the code assignments, we merged or deleted the code categories accordingly. Then, we reviewed all transcripts for final verification of correct code assignments. This procedure resulted in one final coding scheme for each stakeholder category and country, i.e., a total of six coding schemes. Finally, we assigned each code to an appropriate TIS dimension for an empirical operationalization of the TIS framework. The results section presents the analysis for each TIS dimension, including the QI and social perspective as sub-dimensions based on this operationalization (Table 2). Our qualitative research design allows for an in-depth TIS analysis of the hydrogen economy

<sup>3</sup> Note: For data protection reasons, information about the interviewees is fully anonymized.

<sup>4</sup> Note: The coding schemes were independently validated by two authors of this study and one external researcher.

**Table 1 – Sample description.**

Country	Stakeholder category	Type of actor	Value chain (where applicable)
Germany	Industry	Two conglomerate companies	Production, storage, transport, application
		Electrolyzer company	Production
		Vehicle manufacturer	Application
	Policy	Two government agencies	
		Consultancy	
	Society	Three research institutes	
South Korea	Industry	Conformity assessment body	
		Two conglomerate companies	Production, application
		Electrolyzer company	Production
		Tube vessel manufacturer	Storage, transport
	Vehicle manufacturer	Application	
	Policy	Two government agencies	
		Research institute	
Society	Three research institutes/Universities		
		Conformity assessment body	
		Government agency	

**Table 2 – Empirical operationalization of the TIS framework (based on Markard et al. [40]).**

TIS dimension	Indicator	Operationalization
Actor base and TIS size	Entries/exits	Actor involvement
	Business Development	Strategic role for hydrogen-relevant companies
	Market development	Investment costs and hydrogen price Subsidies and R&D funding Current market size and sectors
Institutional structure and networks	Political and regulatory framework	Motives for hydrogen promotion
		Hydrogen roadmaps and other political drivers
	Value chains and networks	Regulatory measures
		Integration in global value chains
		Hydrogen infrastructure
Safety and quality infrastructure	Collaborations and networks	
	Hydrogen safety	
Expectations, social perceptions and acceptance	Hydrogen readiness of QI	
	Social perception and awareness	
	Perception of hydrogen safety	
	Social acceptance, acceptance measures	
Technology performance and variation	Performance and variation	Technology leadership and readiness Degree of variation
	Research & development	Publishing, patenting, and standardization activities
TIS-context relationships	Technological context structures	Relationship to other technologies by sectors
	Wider context	War in Ukraine, energy security Impact on the hydrogen economy

with previously unexplored insights. However, we are aware of the limited representativeness of the expert assessments due to the small sample size of 24 (see Refs. [59,60]). Therefore, we validated and extended, where appropriate, our results with the findings from previous research.

## 4. Results and discussion

This section analyzes and discusses the hydrogen technological innovation systems (TIS) of Germany and South Korea. The sub-chapters dedicated to each country follow the TIS dimensions (Section 2.1), incorporating the quality infrastructure (QI) into the TIS's institutional structure. We assessed each TIS dimension from the perspectives of the above-described industrial, political, and social stakeholder categories, representing the TIS actor base. Additionally, we

consulted relevant previous research to validate and supplement our analysis.

### 4.1. Hydrogen TIS in Germany

Germany has a long history of hydrogen use in industry and the energy sector and has recently attached great importance to this versatile energy carrier for the energy transition and improving energy security. This momentum is reflected in the aim of Germany's hydrogen economy of decarbonizing hard-to-abate sectors while ensuring economic viability through a global leadership position in hydrogen technology development.

#### 4.1.1. Actor base and TIS size

Guided by the potential of a hydrogen economy for economic growth and the energy transition, numerous private-sector

companies along the hydrogen value chain, federal ministries, and research institutes have expanded their scope of activities and commitment to hydrogen technologies as existing or new TIS actors in recent years [6,19,43,61,62]. Hydrogen stakeholder platforms such as the *Research Network Hydrogen* [63] are being established, and the hydrogen discourse is expanding in Germany [64].

While the interviewed companies (*industry perspective*) acknowledged the strategic importance of hydrogen technologies to future business viability, the interviews revealed several barriers to adopting hydrogen technologies on a commercial scale. These include financial ones, particularly high investment and unit manufacturing costs but also demand shortages, lack of available infrastructure, and favorable policy mixes. These findings are consistent with previous studies [65,66] analyzing the barriers for German hydrogen-relevant companies to upscale production or adopt hydrogen technologies.

Therefore, the hydrogen market in Germany does not yet sustain itself. Instead, most hydrogen-related R&D activities are driven by government funding, e.g., through the *National Innovation Program Hydrogen and Fuel Cell Technology* with approved funding of €1.7 billion in 2017–2022 [67,68], or EU funding under the EU's *Important Projects of Common European Interest* with €10.6 billion in public funding approved in 2022 [69]. To support further commercialization, previous studies recommend R&D subsidies towards technology optimization and purchase subsidies [17,65]. To this end, the German government already subsidizes up to 80% of expenditures for the construction of HRSs using exclusively 'green' hydrogen and 45% for the construction of electrolyzers supplying HRSs using 'green' hydrogen [70]. As a result, one interviewed company has meanwhile announced to enter mass production of its electrolyzers.

Nowadays, the German hydrogen market is concentrated on processes in the chemical industry and refineries, relying primarily on grey hydrogen [19,61]. However, hydrogen energy and technologies are not yet adopted as widely as targeted. Therefore, German hydrogen policies aim to increase the availability and reduce the price of hydrogen by upscaling electrolyzer capacity [71] to attract demand towards market formation [72]. At the same time, market growth requires further incentives at the institutional level.

#### 4.1.2. Institutional structure

4.1.2.1. *Political and regulatory factors.* Germany's original national hydrogen strategy (2020)<sup>5</sup> and its updated version (2023) specify the political objectives and target sectors of the German hydrogen economy: 1.) The clean-energy transition based on 'green' hydrogen,<sup>6</sup> especially in hard-to-abate industries and refineries, mobility applications with limited electrification potential, e.g., heavy-duty transport, shipping, aviation, and renewable energy storage for electricity

generation; 2.) Economic viability through a globally leading position in hydrogen technology development while meeting sustainability goals; 3.) An emphasis on hydrogen for energy security and reduced dependencies [5,7,8,52].

The interviewees assessed the original hydrogen strategy, including its 38 measures, as guidance on the development of the German hydrogen economy. It signaled the importance of hydrogen energy and facilitated investment decisions. For the industry, "[...] the hydrogen strategy implies that there will be rules to bring market players onto the hydrogen path" (Interviewee industry perspective). However, various interviewees considered the hydrogen strategy as too vague to advance the hydrogen transition, as it did not specify the implementation of measures and the role of social acceptance. This aligns with the findings of Lux et al. [74], who propose an energy supply model that concretizes the hydrogen strategy.

To address these shortcomings, the government published the revised hydrogen strategy in 2023, which formulates more specific targets, sectoral applications, and measures, including the *Hydrogen Acceleration Act*. Additional legislation promoting the German hydrogen economy has been implemented, including the *Climate Change Act* [75], enshrining greenhouse gas neutrality by 2045, and the 2022 revision of the *Energy Economy Act* [76], facilitating hydrogen-infrastructure development. The 2021 *Coalition Agreement* [77] of the governing parties commits to increasing the domestic electrolyzer capacity to 10 GW by 2030. Furthermore, the German government established the *Hydrogen Council* in 2020 as an independent advisory board to support the implementation of the hydrogen strategy.

Yet, the regulatory framework at the EU and national levels is not designed for the widespread use of hydrogen because it "[...] has so far not considered hydrogen as an energy carrier. It only appeared as an additive in natural gas" (Interviewee policy perspective). This regulatory gap poses a barrier to market formation. Previous research [78,79] has shown that missing or hindering regulations hamper the diffusion of hydrogen technologies, e.g., in green hydrogen production and supply.

Nonetheless, the regulatory framework at the EU level is taking more shape [79]. The green hydrogen taxonomy published in the *Renewable Energy Directive (RED) II Delegated Acts* under the RED (EU) 2018/2001 [80] is expected to boost hydrogen production and market demand. Furthermore, the EU's provisional agreement on the third amendment to the RED stipulates that the industry must raise the total share of hydrogen used to 42% of 'green' hydrogen by 2030 and 60% by 2035 [81]. The interviews revealed that a regulatory framework is vital to give guidance on the direction of technology development and facilitate investment decisions. Therefore, the *Reallabore der Energiewende* demonstration projects at the national level [82], among others, identify new regulatory requirements based on R&D. Moreover, the updated hydrogen strategy enshrines expedited planning and approval procedures as a target of regulatory adjustments.

The guiding character of hydrogen regulation has also been highlighted in studies for other geographical contexts: Chantre et al. [20] emphasize the importance of regulation to reduce uncertainty for market players in the Brazilian hydrogen economy and promote market growth. Likewise, Ikonniva

<sup>5</sup> Note: Also, the EU adopted a hydrogen strategy in 2020 with similar target sectors but slightly different goals [5,73].

<sup>6</sup> Note: The updated hydrogen strategy additionally considers hydrogen colors other than green hydrogen for the duration of the transition period, including grey, blue, and turquoise hydrogen.

et al. [83] show that regulations can stimulate the growth of the international hydrogen market.

**4.1.2.2. Value chains and networks.** The updated hydrogen strategy projects the demand for hydrogen in Germany to reach 95 to 130 TWh by 2030, with 50–70% estimated to be imported [52], resulting in a strong dependence on global value chains [61,84]. The federal government has signed various bilateral agreements on the import of ‘green’ hydrogen with other countries [85,86] and established the *H2Global Foundation* to foster global partnerships towards an international hydrogen value chain [87]. While global value chains enable the exploitation of comparative advantages in green hydrogen production, Van De Graaf et al. [13] and Eicke and De Blasio [84] emphasize the associated geopolitical dependencies that may arise. The authors argue that despite the technical possibility of producing hydrogen in many parts of the world, the comparative advantage in ‘green’ hydrogen production is distributed unequally [13]. Therefore, hydrogen imports from non-EU countries could bear risks of new dependencies and vulnerability for Germany [19]. To this end, the updated hydrogen strategy enshrines reduced dependencies on a future hydrogen supply chain as one of the objectives [52].

However, European and national-level unbundling regulations still create barriers to expanding the hydrogen infrastructure [79,88]. Various endeavors at the national and European levels aim to remove these barriers. The updated hydrogen strategy specifies facilitated planning and approval procedures for accelerated infrastructure expansion, including expanding the German hydrogen pipeline network to 1800 km and the European network to 4500 km [52]. At the EU level, the *Alternative Fuel Infrastructure Regulation* aims to support the EU-wide expansion of HRS infrastructure [89]. Following previous studies [20,83] and our results, favorable regulatory developments are pivotal to fostering the expansion of markets and accordant value chains.

At the level of actor collaborations, various networks have been formed in recent years in the German hydrogen TIS, including the *Research Network Hydrogen* [63], the *HYPOS Network* [90], and the government-funded joint venture *H2Mobility* for the expansion of HRS infrastructure [91]. These networks strengthen stakeholder dialogue and cooperation while intensifying knowledge and technology transfer [6]. As Lopolito et al. [16] show, network creation is particularly important in sustainability transition processes for accelerated niche evolution. The interview findings confirm the pivotal role of hydrogen-relevant networks in bringing together relevant stakeholders with the common goal of advancing the German hydrogen economy.

**4.1.2.3. Safety and quality infrastructure.** In Germany, hydrogen energy has been safely used for decades in the industry and as a component of the town gas mix in the power sector until 1996 [92–94]. Accordingly, standards, regulations, and directives have been in place to ensure safety. For instance, the EU’s *Pressure Equipment Directive* [95] and *ATEX Directive* [96], among others, formulate the essential safety and health requirements applicable to storage containers in HRSs. Standards referenced in the *Official Journal of the European Union*

give substance and indicate compliance with these essential requirements, e.g., EN 1127-2:2014 in the case of ATEX [97]. Notified bodies, i.e., designated conformity assessment bodies, verify with their services compliance of the products with the essential requirements of ATEX. Finally, market surveillance authorities have the right to sanction or even ban unsafe products from the market [50,96,98]. While QI has already been vital in ensuring hydrogen safety, the German and European QI systems are not explicitly designed for the widespread use of hydrogen [61,79].

Instead, most regulations and directives address gases in general or hydrogen as an additive. However, quality assurance and safe hydrogen use in the future hydrogen economy will require a fit-for-purpose QI. In line with previous research, which has outlined the vital role of QI for sustainable development, e.g., by incentivizing sustainable production and consumption or by creating trust in novel, cleaner technologies [45,99,100], QI will be a vital pillar of the hydrogen transition. The German hydrogen strategies have identified QI and its elements as essential for the safe production, storage, transport, and use of hydrogen. The government-funded *Standardization Roadmap Hydrogen Technologies* project, led by the German Institute for Standardization (DIN), aims to implement a sophisticated QI fit for the hydrogen economy, with an emphasis on standards at the heart of QI [101]. Furthermore, the roadmap aims to align with standardization at the European and international levels to enable integration into a global hydrogen economy. At the European level, the *CertifHy* initiative is developing a hydrogen certification scheme, which tracks the origin and sustainability of hydrogen, and lays the groundwork for conformity assessment services [4,102]. Similar to previous studies, which have identified standards and certification schemes as supporting the hydrogen transition [2,6,103], the interviewees emphasized the importance of a hydrogen QI. Among others, QI facilitates social acceptance based on safety, trust, and sustainability [6,58,104,105].

**4.1.2.4. Expectations, social perceptions and acceptance.** While the industrial and political interview perspectives assess the economic and ecological potential of hydrogen technologies as promising (see Sections 4.1.1 and 4.1.2), we add the social perspective for a more sophisticated assessment of the hydrogen TIS. This allows us to explore whether the targeted diffusion of hydrogen technologies, which can increase public exposure, e.g., to HRSs, already finds general acceptance in society.

In line with previous research [43,106], the interviewees representing the *social perspective* assess the social perception of hydrogen technologies in Germany as largely positive, given the potential for energy transition and energy security.<sup>7</sup>

However, this results from the public’s knowledge being limited and dominated by the perceived benefits and limited exposure and experience. Therefore, the positive perception is abstract based on the low salience of hydrogen technologies, which Emodi et al. [105] have also found in the review of social

<sup>7</sup> Note: The perspectives were given based on the interviewees’ findings from conducted studies, local community work, workshops, etc. with the ‘people’.

acceptance across various countries. Simultaneously, safety concerns reflected in the ‘not-in-my-backyard’ (NIMBY) issue remain a barrier to social acceptance in Germany, as also addressed in previous research [43,106,107]. However, safety concerns are rather based on negative associations than personal experience. Therefore, the interviewees emphasized that social acceptance is highly dynamic and that safety-related events can substantially deteriorate acceptance, depending on their magnitude and impact on society. To create more sustained social acceptance, the interviewees recommend increasing the public's knowledge base through comprehensible and transparent communication about the safety and benefits of hydrogen. This result is consistent with the findings of Gordon et al. [106], Huijts et al. [108], and Schmidt and Donsbach [23], showing that information provision is associated with a more positive public perception of hydrogen. However, according to the interviewees, awareness raising is currently concentrated on demonstration projects open to interested individuals without sufficiently targeting the general public.

Besides, we identified further determinants of social acceptance, including the costs, infrastructure availability, sustainability, perceived usefulness, and alignment of hydrogen technology adoption with personal and behavioral traits. With that, our findings are consistent with previously identified acceptance factors in other research contexts [62,105,106,109–111].

Hence, increasing the attractiveness of hydrogen technologies along these acceptance factors while securing safety and imparting relevant knowledge can be considered factors favoring TIS development, especially for applications with social proximity.

#### 4.1.3. Technology performance and variation

Due to knowledge and technology spillovers beyond geographical boundaries, we acknowledge that the *technology performance and variation* dimension cannot be entirely truncated to the national level [32,112]. Thus, we assess this TIS dimension based on the interviewees' assessment and the findings from previous research specific to Germany.

As one of the leading countries in hydrogen production and storage technologies, Germany is engaged in extensive R&D activities [6,113,114], shows a high technology readiness level, especially in industrial processes [113,115], and aims to become a technology-leading country along the whole value chain [52,79]. However, the interviewees revealed the potential for technology optimization toward reduced design variation. This finding corresponds to the worldwide trend described in previous research, with high variation in hydrogen production methods, feedstocks for production [116,117], or hydrogen-storage options [118–120].

Within the scope of corporate R&D activities, patents, standards, and to a lesser extent, publications represent both inputs and outcomes [6,121–124]. In line with previous research, we regard these knowledge and technology transfer channels as TIS performance indicators and analyzed their role in hydrogen-related R&D within the interviewed companies [6,122]. All interviewees confirmed their participation in hydrogen standardization, primarily to ensure safety but also for economic reasons linked to upscaling production,

market development, and to establish common ground for stakeholder collaboration. Regarding patenting, the primary motives are to protect intellectual property rights, economic gain, and address safety matters. In contrast, publishing is closely linked to collaborations with academia. Here, the objectives are optimized technology development based on scientific results and more visibility in the scientific community. However, for its limited marketability, publishing is not the focus of corporate R&D. Herewith, our findings contradict the results of Blind et al. [122], who analyzed the motives of engineers in the German automotive sector to engage in publishing, patenting, and standardization activities. Our results demonstrate that standardization at the corporate level, rather than at the employee level analyzed by the authors, is not mainly driven by intrinsic motivation. In contrast, our publishing and patenting results largely align with theirs [122].

#### 4.1.4. TIS-context relations

This section analyzes the TIS-context relations for each relevant target sector of the German hydrogen economy following the original and updated versions of the hydrogen strategy.

In the decarbonization of heavy industries, the limited potential for electrification has brought hydrogen into focus to significantly reduce emissions [5,64]. However, several interviewees, in line with previous studies [125,126], call for incurring the costs of fossil fuels through carbon pricing while reducing the hydrogen price. Otherwise, the industry will have little incentive to replace fossil-based industrial processes with hydrogen energy. Therefore, hydrogen use in the industry is currently concentrated in niche applications and dominated by the context structures [30,64].

In mobility, the German hydrogen strategies enshrine heavy-duty vehicles, shipping, and aviation as main applications. While passenger vehicles are mentioned as further options, the new strategy prioritizes direct electrification, where more appropriate and energy-efficient, and hydrogen solutions in areas with limited electrification potential [5,52]. Since FCEVs currently represent a niche application in mobility compared to internal combustion engine and increasingly to battery-electric vehicles [65], one interviewee called for technology-neutral policies that could favor hydrogen solutions for specific mobility applications. Similarly, Yuan and Cai [127] postulate that promoting low-emission vehicles, including FCEVs, requires more technology-neutral approaches. This could shift the TIS-context relations in mobility towards the adoption of hydrogen technologies.

In the electricity sector, according to the hydrogen strategies, hydrogen will be relevant as an energy storage medium to reduce seasonal fluctuations in renewable energy availability. However, the updated hydrogen strategy attaches limited importance to hydrogen use in heating, starting from 2030 in pilot projects. Instead, policies appear to prioritize direct electrification in this sector, e.g., via heat pumps [5,8,52].

Nonetheless, we cannot preclude that widespread hydrogen technology adoption in passenger vehicles and heating could evolve as new development paths in the future [30,112], which would create proximity to the public. Against this backdrop, creating social acceptance becomes even more critical.

Regarding the geographical context structures, the disruption in the natural gas supply following the war in



Ukraine has boosted the German hydrogen economy. To reduce the dependence on fossil fuel imports from Russia and ensure a stable, sustainable energy supply, the *REPowerEU Plan* (2022) prescribes the increase of domestic production of ‘green’ hydrogen to 10 million tons and the import of 10 million tons of hydrogen annually by 2030 [4,128]. The updated hydrogen strategy underscores Germany’s ambition to transition to a hydrogen economy to reduce dependencies while advancing its economic and climate policy goals.

The TIS-context relations demonstrate that hydrogen technologies are currently in the technological niche. However, they are gaining momentum in light of Germany’s sustainability and energy security targets. Thus, we expect the hydrogen TIS to gain importance in relation to its context structures in the future.

## 4.2. Hydrogen TIS in South Korea

South Korea’s motive to build a hydrogen economy stems from the country’s ambition to establish itself as a technology-leading country in the development of hydrogen technologies. This ambition is reflected in the country’s success in commercializing fuel cells and FCEVs, with mobility and the power sector historically representing important pillars of South Korea’s hydrogen economy.

### 4.2.1. Actor base and TIS size

Similar to Germany, the South Korean hydrogen TIS has attracted a wide range of stakeholders, as reflected in the composition of members of the government-led private consultative body *H2KOREA*, which serves as an institutional platform to advance the hydrogen economy [129]. According to previous research, government policies have incentivized actor involvement in the South Korean hydrogen sector, e.g., through funding for research and technology development under the *National R&D Program* [130,131]. In contrast, the interviewees indicated that their decision to enter the hydrogen industry was primarily driven by economic motives. Nonetheless, they acknowledged that government policies have provided economic incentives to facilitate this decision. For instance, the government grants a 50% purchase subsidy for FCEVs and a minimum 50% coverage of costs for constructing and operating HRSs [7,12]. This policy promotion has helped South Korea develop the largest FCEV market worldwide, with a global share of approximately 40% of all FCEVs in stock [4]. South Korea’s *Hyundai Nexa* is the top-selling FCEV worldwide and the only commercialized FCEV, along with Japan’s *Toyota Mirai* and *Honda Clarity* [119,132]. To promote further market growth, the interviewed experts emphasized the need for increased hydrogen availability to reduce its price and attract more demand, especially through imports. This conclusion is further supported by previous research in the South Korean context [11,12].

To increase domestic hydrogen production and competitiveness, the government additionally provides funding for sustainable hydrogen production and use (see Section 4.2.2). However, high investment costs hinder most hydrogen-relevant companies from upscaling their production capacities. In contrast, one interviewed company has already realized profits due to high domestic demand as the primary

supplier of storage containers for HRSs in South Korea, which have received substantial government support. This finding is consistent with previous research [125], confirming that subsidies are an essential policy tool to initiate growth in the early phases of the hydrogen economy by making the hydrogen business profitable and attracting new TIS actors to enter.

### 4.2.2. Institutional structure

4.2.2.1. *Political and regulatory factors.* The *Hydrogen Economy Roadmap* and *National Roadmap of Hydrogen Technology Development* released in 2019, as well as the new hydrogen policies announced by the *Hydrogen Economy Commission* in 2022, define the objectives and target sectors of South Korea’s hydrogen economy: 1.) Economic growth driven by technology leadership and national competitiveness motives, as well as reduced greenhouse gas emissions to achieve carbon neutrality by 2050; 2.) Energy security reflected in the openness to relying on hydrogen produced from various feedstocks, including ‘green’ and ‘blue’ hydrogen produced from natural gas with CCUS; 3.) A focus on the mobility and power sectors. By 2040, the government targets a domestic stock of 2.9 million FCEVs alongside 3.3 million exported FCEVs, as well as domestic use of 8 GW stationary fuel cell power for central power generation (plus 7 GW for exports) and 2.1 GW for decentralized power generation [5,7,12,133,134].

According to the interviewees, hydrogen policies have been pivotal in signaling the importance of hydrogen technologies to the South Korean economy. As one interviewee (Industry perspective) explained, “without the policy direction, we wouldn’t have been able to enter the hydrogen industry.” Besides the roadmap, the government has created the legal basis for a hydrogen economy by adopting the *Hydrogen Economy Promotion and Hydrogen Safety Management Law* (2020). This Law offers a supportive scheme to expand the hydrogen economy and particularly addresses safety [135]. Furthermore, it creates the legal basis for standards and certification schemes to promote the diffusion of hydrogen technologies [136]. Amendments to the Law include the *Renewable Energy Certificates* (REC) issued for power generation from fuel cells and the *Clean Hydrogen Portfolio Standard* (CHPS) certification scheme, which will be adopted by 2024 to subsidize the production and use of clean hydrogen [4,136].

While regulatory measures can play a guiding role and reduce uncertainty for stakeholders following the TIS framework [30], interviewees from different perspectives indicated that national regulation imposes too stringent safety requirements, e.g., safety distances for HRSs or application-specific certifications of storage containers. Therefore, both policymakers and the industry have recognized the necessity for balancing safety and technology development. Our findings indicate that, besides the degree of structuration of the hydrogen TIS, its suitability to the needs and requirements of market participants also matters.

Accordingly, the government has established regulatory sandboxes, which grant selected companies a two-year exemption from regulations to identify new regulatory and standard needs and potential deregulation based on R&D [12,129]. With that, regulatory sandboxes contribute to optimized hydrogen regulation based on experimentation [78]. Similarly, Beckstedde et al. [137] show that regulatory

sandboxes play an increasing role in the European context and help promote innovation and market integration in the energy sector. Therefore, they represent a pivotal instrument in advancing the hydrogen TIS's institutional structure across countries.

**4.2.2.2. Value chains and networks.** Similar to Germany, the South Korean economy depends on energy imports. Coupled with uneconomic domestic renewable energy generation, domestic hydrogen production at a competitive price is limited [11,12]. Therefore, the government aims to meet 70% of domestic hydrogen demand through domestic production and substantial overseas imports by 2040 [5,9]. These targets have been further nurtured by the new government policies of the *Hydrogen Economy Commission* (2022), including the establishment of a global hydrogen value chain and the expansion of HRS infrastructure, supported by the removal of business-hampering regulations [134].

Moreover, South Korea has launched the *Global Hydrogen Industrial Association Alliance* (GHIAA) with 17 member states and the EU to foster international collaboration, including hydrogen imports to South Korea [138]. In the future, South Korea aims to deliver imported hydrogen via pipelines directly from the points of import to downstream applications, e.g., HRSs, to facilitate hydrogen use [12]. In preparation for a sophisticated future value chain, South Korea is advancing the feasibility of a globally integrated hydrogen economy in designated pilot cities like Ulsan [129].

While dependence on hydrogen imports can bear geopolitical risks [13], South Korea considers hydrogen an energy carrier that stabilizes and diversifies the energy supply, thereby reducing dependencies [5,9]. South Korea embraces the use of hydrogen from various feedstocks, which would also enable domestic hydrogen production, e.g., from imported natural gas or ammonia. Therefore, unlike previous studies [13,84], hydrogen imports not only involve geopolitical risks but may also reduce existing dependencies.

In value chains for hydrogen technologies, the interviewees stated that national safety standards pose a barrier to importing non-compliant foreign technology components. Against the backdrop of South Korea's objective of becoming a hydrogen technology-leading country, the interviewees indicated that harmonization with international standards would facilitate integration into a global hydrogen value chain. This finding is consistent with the results of previous studies [49,139,140], showing the positive effect of harmonized international standards and the negative effect of purely national standards on international trade.

To advance the domestic hydrogen economy, various networks have been created in recent years. One example is H2KOREA, which fosters exchange and collaboration among hydrogen stakeholders through its member network [129]. Additionally, the collaboration of companies within the government-led consortium HyNet has enabled South Korea to become one of the countries with the most HRSs worldwide, with 167 units as of 2022 [4,12]. These networks demonstrate an increasing structuration of the TIS and coordination of TIS actors. Thus, we confirm the importance of stakeholder networks in guiding sustainability transitions, as demonstrated by Lopolito et al. [16].

**4.2.2.3. Safety and quality infrastructure.** The explosion of a hydrogen storage container in the city of Gangneung (2019) marked a turning point in national hydrogen safety management [141]. Following the accident, the 2020 Safety Law was adopted to codify and enforce hydrogen safety, amended by safety standards, certification schemes, and monitoring systems [135,136]. With the Law, South Korea laid the basis for strengthening hydrogen QI, in which the *Korea Gas Safety Corporation* (KGS) plays an essential role. As a government authority for safety management, KGS develops safety regulations and standards for hydrogen technologies in South Korea, delivers conformity assessment services, including testing, inspection, and certification, and acts as a market surveillance authority [141]. Based on insights from various interviews, KGS develops regulations and standards for HRSs, issues permissions for their construction and operation, monitors them through the KGS monitoring center and has the authority to shut them down if potential hazards are detected. While KGS is the main player in the national hydrogen QI, other notified conformity assessment bodies or the *Korean Agency for Technology and Standards* (KATS) must also be mentioned as QI players. Thus, South Korea has implemented vital QI elements designed for its hydrogen economy targets. Towards their achievement, the Korean hydrogen QI serves the purpose of ensuring safety through high standards and promoting sustainability through the REC and CHPS certification schemes. Particularly, since South Korea's hydrogen economy relies on target sectors in proximity to the public, the hydrogen QI aims to create social acceptance and trust based on safety.

However, the regulatory revisions and the experimentation-based identification of new regulatory requirements (regulatory sandboxes) provide evidence that the hydrogen QI is still under development. Therefore, drawing from previous research on the role of QI for sustainable development [45,99,100], a fit-for-purpose hydrogen QI will aid South Korea in its transition to the hydrogen economy. This link is also consistent with previous studies emphasizing the significance of safety and acceptance, which QI enhances, in fostering hydrogen market growth [2,58].

**4.2.2.4. Expectations, social perceptions and acceptance.** Supported by the political agenda, the interviewed industry experts emphasized the potential of hydrogen technology adoption for long-term business viability. Besides the industrial and political perspectives, the targeted penetration of hydrogen technologies in the mobility and power sectors creates proximity to society. Therefore, the social perception and acceptance levels are critical for realizing the hydrogen transition and, thus, facilitating TIS development.

The interviewed experts (*social perspective*) assessed the hydrogen perception in South Korea as largely positive.<sup>8</sup> Particularly, we identified future orientation and sustainability awareness as drivers, which Scovell [111] also found previously. Acceptance is even higher when individuals can increase

<sup>8</sup> Note: The assessments were based on the interviewees' research on the social acceptance of hydrogen technologies in Korea by means of surveys, workshops, media report analyses, etc.

their utility by using hydrogen technologies and aligning it with their personal and behavioral traits, needs, and values [111,142,143]. Furthermore, knowledge, experience, perceived costs, and risks drive acceptance [111,142,144]. Hence, the findings from previous research validate our results.

The current state of the South Korean hydrogen economy addresses some of these acceptance factors through its highly developed hydrogen mobility sector, exposing the public to hydrogen technologies. Moreover, government subsidies for hydrogen applications tackle the cost dimension, making them competitive with other technologies (Section 4.2.1).

However, several issues hinder social acceptance in South Korea: The Gangneung accident, accompanied by untransparent, negative media reports, has created an anxious perception among parts of the public [145], reinforcing the NIMBY issue, particularly for HRSs. In the words of one interviewee, people "[...] are very opposed to installing them [HRSs] near their area. About two years ago, or a year ago, about 70 to 80 percent of the sites that were planned [...] were nullified due to the constant opposition of the residents" (Interviewee industry perspective). Based on a public survey in South Korea, Han et al. [146] also found that 23% of respondents were opposed to the construction of HRSs near their residences. These findings illustrate that public opposition to hydrogen technologies can indeed hinder the hydrogen transition.

QI, which creates social acceptance and reduces public reservations based on safety, is critical to the success of a hydrogen economy, particularly when situated in proximity to the public. Besides safety, the interviewees and previous research [111,142,145] agree that increasing the public's knowledge base through transparent communication can increase acceptance. For instance, the South Korean government relies on social media and community-briefing sessions to raise awareness.

#### 4.2.3. Technology performance and variation

South Korea is one of the technology-leading countries in FCEV and stationary fuel cell innovation, as evidenced by extensive patenting activities [6,119,132,147]. As an early adopter, South Korea aims to establish a domestic lead market for FCEVs and stationary fuel cells to gain a competitive advantage in a future global hydrogen economy (see Refs. [133,148,149]). Moreover, the new policy direction of the *Hydrogen Economy Commission* postulates the promotion of technology development along the whole value chain toward a leadership position as a technology-exporting country [134].

Despite South Korea's technological advances, the interviewees indicated the potential for further technology optimization, e.g., in the area of on-board hydrogen storage for FCEVs. Since South Korea has substantially shaped past technological trends in FCEVs, previous research validates the optimization potential, including more advanced storage options like higher-pressure gaseous or liquefied storage [119]. To maintain a globally leading position in the future, national R&D budgets and the CHPS certification scheme, among others, allocate funds to technology optimization (Section 4.2.1), which will likely result in reduced design variation following the TIS framework [30].

As with the German TIS, we identified the motives and barriers of the interviewed companies to publishing,

patenting, and standardization [6,122]. All interviewed companies stated their involvement in hydrogen standardization at the national or international levels, primarily to address safety with other stakeholders, to optimize technology development, and to harmonize standards. For patenting, we identified protecting intellectual property rights rather than addressing safety as the primary motive. Publishing activities result mainly from industry-academia collaborations, which facilitate knowledge and technology transfer, and increase the visibility of companies in the scientific community (see also [6,122,150]). However, publishing is not the main objective of R&D activities and is constrained by limited human resources. These findings differ from those of Blind et al. [122], who attribute participation in standardization to intrinsic motivation, while the interviews revealed technical and commercial objectives as drivers. For patenting and publishing, the results are largely consistent with Blind et al. [122].

#### 4.2.4. TIS-context relations

This section analyzes the TIS-context relations from the perspectives of the mobility and power sectors as target sectors of the South Korean hydrogen economy. In mobility, the government promotes FCEVs and battery-electric vehicles to transform this sector sustainably. Electric vehicles and the construction of charging infrastructure are supported by subsidies [151,152], while the government gradually reduces them to foster sustained market growth. Simultaneously, the high subsidies for FCEVs aim to expand the FCEV market and enable the complementarity of both powertrain technologies in mobility, thereby taking a more technology-neutral approach following Yuan and Cai [127].

In the power and building sectors, fossil fuels and nuclear energy dominate as context structures. In 2021, 85% of primary energy in South Korea was based on fossil fuels [153]. Therefore, the interviewees called for incurring the costs of fossil fuels to advance the hydrogen transition. The CHPS, designed to subsidize clean hydrogen production and use, is expected to enhance the competitiveness of fuel cell power generation and FCEVs with the incumbent fossil fuel-based technology regime [147]. Further support is provided by the target set by the *Hydrogen Economy Commission* to increase the share of clean hydrogen in the energy mix to 7.1% by 2036 [134]. Following previous research [125,126], policy instruments such as the CHPS, which incentivize the transition to cleaner energy, will be pivotal in the hydrogen transition.

In the geographical context structures, the global energy crisis has exposed South Korea's dependence on energy imports. Subsequently, according to various interviewees, securing energy supply through hydrogen has gained even more importance. However, the energy crisis adversely affected the hydrogen economy in the short run. Due to the global increase in natural gas prices, the 'grey' hydrogen costs experienced a threefold increase in 2022 [4]. Since the hydrogen economy nowadays relies primarily on 'grey' hydrogen, the interviewees revealed that the high costs reduced hydrogen production and supply, e.g., at HRSs. Following previous studies on the geopolitics of hydrogen [13,84], this result provides evidence that diversifying the feedstocks for hydrogen production, as considered by South Korean hydrogen policies, can help reduce dependencies.

While hydrogen technologies are still a niche technology, South Korean policies have given various supportive signals to promote the hydrogen economy. Therefore, we consider the TIS-context relations as dynamic with a possible future shift towards the focal hydrogen TIS.

## 5. Conclusion and implications

This study has explored the technological innovation systems (TISs) of Germany and South Korea from the perspectives of industry, politics, and society (RQ1). Both countries' hydrogen innovation systems show common features but also differences across various TIS dimensions (Table 3): While the actor base, which is more state-centered in South Korea, is expanding in both countries, the hydrogen market is more developed in South Korea, especially in mobility. The institutional structure, including the regulatory framework and quality infrastructure (QI), is taking increasing shape at the German and European levels while already showing greater maturity in South Korea. For social acceptance, we also identified a more sustained acceptance level in South Korea than in Germany, where public awareness of hydrogen technologies is limited overall. In technology performance, Germany and South Korea hold globally-leading positions but in different parts of the value chain. Technology variation in both countries is largely consistent with the worldwide trend, while the TIS-context relations appear more favorable to the hydrogen TIS in South Korea.

Assessing the life cycles of Germany's and South Korea's TISs (RQ2) following Markard [30], the German hydrogen TIS can be considered to be in the late formative phase based on the TIS dynamics and the expected advances in the regulatory framework, QI, and market size. In contrast, the South Korean

hydrogen TIS appears more mature regarding the legal framework, QI, market size, and social awareness, thus exhibiting more growth phase properties.

This study contributes to previous research at multiple levels: First, following Andreasen and Sovacool [34], comparing the hydrogen economies of two countries based on the TIS framework enables a more sophisticated assessment of the status and drivers of the hydrogen economy. Especially by deploying the TIS life-cycle approach [30], we add to the toolbox of concepts to assess the maturity of a hydrogen economy from various perspectives. Unlike previous hydrogen TIS research, which considers only the hydrogen TIS within sectoral or application boundaries, such as for the steel [24,26] or automotive industry [25,34], we assess the hydrogen TIS more comprehensively by analyzing and discussing the drivers and barriers to Germany's and South Korea's pathways to the hydrogen economy. Second, we added the social perspective on hydrogen technology adoption, which was hardly considered in previous hydrogen TIS analyses. Although an increasing body of research on the social acceptance of hydrogen technologies has emerged in recent years [43,44,111,146], previous studies do not analyze it in the broader context of the hydrogen economy and hydrogen TIS.

This study synthesized the perspectives of key stakeholders, including those from society, industry, and policy-making. This multidimensional analysis of the hydrogen TISs in Germany and South Korea provides meaningful policy implications potentially transferable to other contexts (RQ3): First, greening the financial system will be crucial to make hydrogen technologies more competitive. As our analysis has shown, the high costs of hydrogen technologies and their limited competitiveness with the established fossil-based technology regime represent major barriers to the hydrogen economy. Following previous studies, policymakers should

**Table 3 – Comparison of hydrogen TISs.**

TIS dimension	Germany	South Korea
Actor base and TIS size	Increasing actor involvement, intermediate government role R&D funding, demonstration projects, partly reimbursement of 'green' HRS costs and electrolyzers Market concentrated in industrial niches	Increasing actor involvement, strong government influence R&D funding, incentives for commercialization (purchase subsidies), partly reimbursement of HRS costs Largest FCEV market worldwide
Institutional structure	National & EU Hydrogen Strategies Regulatory framework under development Domestic hydrogen production, but largely imports  Hydrogen QI under development Positive social perception, limited awareness, NIMBY	Hydrogen Roadmaps & Hydrogen Law Regulatory framework in place, revisions Limited hydrogen production capacity, largely hydrogen (feedstock) imports Hydrogen QI largely in place, safety regime Positive social perception, more sustained acceptance, NIMBY
Technology performance and variation	Promotional activities (social acceptance) primarily in demonstration projects Activities along the whole value chain  Patenting and standardization driven by safety and economic motives, publishing is secondary	Government-driven promotional activities (social acceptance) Focus on downstream applications, recent extension to the whole value chain Patenting and standardization driven by safety and economic motives, publishing is secondary
TIS-context relations	Dominance of context (fossil fuels) Targeted promotion in the industry, energy storage and selected mobility applications (currently niche) Energy crisis push, new 'green' hydrogen targets	Dominance of context (fossil fuels, nuclear energy) Targeted promotion of passenger vehicles and power generation (currently niche) Energy crisis push, short-term adverse effect on 'grey' hydrogen supply

cut subsidies for fossil fuels and fossil-based technologies, accompanied by a substantial increase in taxes on them and allocation of increased tax revenue to green innovations and the reduction of their costs, including hydrogen technologies [125,154–156].

Second, following Cervantes et al. [155], changes in science, technology, and industrial policies are necessary based on coherent policy mixes, political commitment, financial instruments, and adaptation of the regulatory framework to the targeted diffusion of hydrogen technologies. Given the emerging nature of the hydrogen economies of Germany and South Korea, our analysis demonstrated that regulatory sandboxes can offer a suitable tool for identifying and demonstrating the necessary regulatory requirements in both the revision (South Korea) and the implementation of new regulations (Germany).

Third, in line with previous QI-related studies [45,99,100], a fit-for-purpose QI is essential to ensure safety and reliability, thereby creating trust and social acceptance of hydrogen technologies. This involves strategically driving the development of a regulatory framework, standards, testing procedures, and certification. Given the challenges of monitoring the safety of hydrogen technologies at scale, the institutions, tools, and processes of QI must be able to keep pace with the requirements of modern hydrogen systems. Therefore, a trustworthy QI relying on digital technologies enhances the safety, transparency, reliability, and economic viability of hydrogen systems, e.g., through real-time monitoring and remote predictive maintenance [157]. Developing a digital QI, including digital methods and tools such as machine-readable standards or digital certificates, requires appropriate government coordination of central QI institutions. An accordant initiative ('QI-Digital') has been implemented in Germany, including joint projects with South Korea for HRSs [157].

Fourth, policymakers should promote public awareness raising in the form of increased knowledge and experience with hydrogen technologies [106,108,111]. In the case of potential incidents or accidents, proactive awareness raising can help mitigate adverse acceptance effects with potential repercussions for the whole hydrogen TIS.

Finally, fostering collaborations at the national and international levels and between informal and institutional actors represents another relevant area for policymaking [20,155,158]. Our analysis has shown that collaborations, including consortia, industry-academia collaborations, or aligning standards through international standardization, are important for establishing a hydrogen value chain and infrastructure, intensifying knowledge and technology transfer, and facilitating the hydrogen transition. Policymakers can foster these collaborations by providing common platforms for stakeholder exchange, similar to the *Research Network Hydrogen* in Germany or *H2KOREA* in South Korea.

This study is not without limitations. First, given the qualitative research design of this study, the sample of interviewees limits the representativeness and generalizability of stakeholder perspectives. Second, open coding yields the risk of subjectivity bias when assigning codes to the interview transcripts and operationalizing them to the TIS dimensions. To minimize bias, the coding schemes were

revised multiple times and reviewed independently by the authors. Third, while this study provides multidimensional TIS perspectives analyzing three major stakeholder categories, the analytical depth per category is limited. Finally, this study represents only a snapshot of the hydrogen TISs in Germany and South Korea. Given the current momentum of the hydrogen economy, we expect further significant developments in the near future.

This study offers prospects for future research: At the empirical level, the identified drivers and barriers can help design structured questionnaires directed to a larger pool of stakeholders and, thus, complement the limited sample size in this study. This would enable quantitative measurements of the progress of national hydrogen economies and accordant country comparisons. Herewith, the sample size, significance, and generalizability of results could be enhanced. Moreover, a survey-based research design would enable more regular updates on the status of the hydrogen economy around the world.

At the theoretical level, future hydrogen-related TIS studies should incorporate, where appropriate, QI and social acceptance more comprehensively. Since the future success of the hydrogen economy will depend, among others, on how well the promise for safety, trustworthiness, and sustainability can be fulfilled, QI acts as an enabler of hydrogen TIS development.

---

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

---

## Acknowledgments

The authors would like to thank the 24 experts for participating in the interviews and their valuable contributions to our research, as well as various colleagues from the H2Safety@BAM Competence Center and Dr. Daniel Weiss, German Aerospace Center, for their helpful comments and support. Parsa Asna Ashari gratefully acknowledges funding by the German Federal Ministry of Education and Research (BMBF) and BAM under "Aufbau einer APRA-Forschungspräsenz für Sicherheitsforschung zur Wasserstoffsicherheit zwischen Deutschland und Südkorea", as well as the H2Safety@BAM Competence Center and the colleagues from H2KOREA for enabling the research visit to South Korea, and thus this research paper.

---

## REFERENCES

- [1] Falcone PM, Hiete M, Sapio A. Hydrogen economy and sustainable development goals: review and policy insights. *Curr Opin Green Sustainable Chem* 2021;31:100506.
- [2] Dincer I, Acar C. Innovation in hydrogen production. *Int J Hydrogen Energy* 2017;42(22):14843–64.

- [3] Cremonese L, Mbungu GK, Quitzow R. The sustainability of green hydrogen: an uncertain proposition. *Int J Hydrogen Energy* 2023;48(51):19422–36.
- [4] IEA. Global Hydrogen review 2022. 2022. Available from: <https://www.iea.org/reports/global-hydrogen-review-2022>.
- [5] Albrecht U, et al. International hydrogen strategies. A study commissioned by and in cooperation with the world energy Council Germany. Ludwig Bolkow Systemtechnik GmbH: Ottobrunn; 2020. Available from: [https://www.weltenergieat.de/wp-content/uploads/2020/10/WEC\\_H2\\_Strategies\\_finalreport.pdf](https://www.weltenergieat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf).
- [6] Asna Ashari P, Blind K, Koch C. Knowledge and technology transfer via publications, patents, standards: exploring the hydrogen technological innovation system. *Technol Forecast Soc Change* 2023;187:122201.
- [7] IEA. Global Hydrogen review 2021. 2021. Available from: <https://www.iea.org/reports/global-hydrogen-review-2021>.
- [8] Bundesministerium für Wirtschaft und Energie. The National Hydrogen Strategy. 2020. Berlin. Available from: [https://www.bmbf.de/bmbf/shareddocs/downloads/files/bmwi\\_nationale-wasserstoffstrategie\\_eng\\_s01.pdf?\\_blob=publicationFile&v=1](https://www.bmbf.de/bmbf/shareddocs/downloads/files/bmwi_nationale-wasserstoffstrategie_eng_s01.pdf?_blob=publicationFile&v=1).
- [9] Ministry of Trade, Industry and energy. Hydrogen Economy Roadmap of Korea. 2019. Seoul. Available from: [https://docs.wixstatic.com/ugd/45185a\\_fc2f37727595437590891a3c7ca0d025.pdf](https://docs.wixstatic.com/ugd/45185a_fc2f37727595437590891a3c7ca0d025.pdf).
- [10] Maennel A, Kim H-G. Comparison of greenhouse gas reduction potential through renewable energy transition in South Korea and Germany. *Energies* 2018;11(1):206.
- [11] Chu KH, et al. Evaluation of strategic directions for supply and demand of green hydrogen in South Korea. *Int J Hydrogen Energy* 2022;47(3):1409–24.
- [12] Stangarone T. South Korean efforts to transition to a hydrogen economy. *Clean Technol Environ Policy* 2021;23(2):509–16.
- [13] Van de Graaf T, et al. The new oil? The geopolitics and international governance of hydrogen. *Energy Res Social Sci* 2020;70:101667.
- [14] Falcone PM. Analysing stakeholders' perspectives towards a socio-technical change: the energy transition journey in Gela Municipality. *AIMS Energy* 2018;6(4):645–57.
- [15] D'Adamo I, et al. Exploring regional transitions to the bioeconomy using a socio-economic indicator: the case of Italy. *Econ Politic* 2022;39(3):989–1021.
- [16] Lopolito A, Falcone PM, Sica E. The role of proximity in sustainability transitions: a technological niche evolution analysis. *Res Pol* 2022;51(3):104464.
- [17] Andreasen KP, Sovacool BK. Energy sustainability, stakeholder conflicts, and the future of hydrogen in Denmark. *Renew Sustain Energy Rev* 2014;39:891–7.
- [18] Andreasen KP, Sovacool BK. Mapping and interpreting critical hydrogen stakeholders in Denmark. *Int J Hydrogen Energy* 2014;39(15):7634–7.
- [19] Schlund D, Schulte S, Sprenger T. The who's who of a hydrogen market ramp-up: a stakeholder analysis for Germany. *Renew Sustain Energy Rev* 2022;154:111810.
- [20] Chantre C, et al. Hydrogen economy development in Brazil: an analysis of stakeholders' perception. *Sustain Prod Consum* 2022;34:26–41.
- [21] Murray M, et al. Stakeholder perceptions towards the transition to a hydrogen economy in Poland. *Int J Hydrogen Energy* 2008;33(1):20–7.
- [22] Seymour EH, Murray L, Fernandes R. Key Challenges to the introduction of hydrogen—European stakeholder views. *Int J Hydrogen Energy* 2008;33(12):3015–20.
- [23] Schmidt A, Donsbach W. Acceptance factors of hydrogen and their use by relevant stakeholders and the media. *Int J Hydrogen Energy* 2016;41(8):4509–20.
- [24] Bach H, et al. Implementing maritime battery-electric and hydrogen solutions: a technological innovation systems analysis. *Transportation Research Part D: Transport and Environment* 2020;87:102492.
- [25] Köhler J, et al. Leaving fossil fuels behind? An innovation system analysis of low carbon cars. *J Clean Prod* 2013;48:176–86.
- [26] Kushnir D, et al. Adopting hydrogen direct reduction for the Swedish steel industry: a technological innovation system (TIS) study. *J Clean Prod* 2020;242:118185.
- [27] Hacking N, Pearson P, Eames M. Mapping innovation and diffusion of hydrogen fuel cell technologies: evidence from the UK's hydrogen fuel cell technological innovation system, 1954–2012. *Int J Hydrogen Energy* 2019;44(57):29805–48.
- [28] Decourt B. Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis. *Int J Hydrogen Energy* 2019;44(33):17411–30.
- [29] Musiolik J, Markard J. Creating and shaping innovation systems: formal networks in the innovation system for stationary fuel cells in Germany. *Energy Pol* 2011;39(4):1909–22.
- [30] Markard J. The life cycle of technological innovation systems. *Technol Forecast Soc Change* 2020;153:119407.
- [31] Binz C, Truffer B. Global Innovation Systems—a conceptual framework for innovation dynamics in transnational contexts. *Res Pol* 2017;46(7):1284–98.
- [32] Binz C, Truffer B, Coenen L. Why space matters in technological innovation systems—mapping global knowledge dynamics of membrane bioreactor technology. *Res Pol* 2014;43(1):138–55.
- [33] Markard J, Raven R, Truffer B. Sustainability transitions: an emerging field of research and its prospects. *Res Pol* 2012;41(6):955–67.
- [34] Andreasen KP, Sovacool BK. Hydrogen technological innovation systems in practice: comparing Danish and American approaches to fuel cell development. *J Clean Prod* 2015;94:359–68.
- [35] Bergek A, et al. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. *Res Pol* 2008;37(3):407–29.
- [36] Bergek A, et al. Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. *Environ Innov Soc Transit* 2015;16:51–64.
- [37] Hekkert MP, et al. Functions of innovation systems: a new approach for analysing technological change. *Technol Forecast Soc Change* 2007;74(4):413–32.
- [38] Stephan A, et al. The sectoral configuration of technological innovation systems: patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. *Res Pol* 2017;46(4):709–23.
- [39] Hekkert MP, et al. Technological innovation system analysis A manual for analysts. 2011.
- [40] Markard J, et al. Destined for decline? Examining nuclear energy from a technological innovation systems perspective. *Energy Res Social Sci* 2020;67:101512.
- [41] Wiczorek AJ, Hekkert MP. Systemic instruments for systemic innovation problems: a framework for policy makers and innovation scholars. *Sci Publ Pol* 2012;39(1):74–87.
- [42] Suurs RAA, Hekkert MP, Smits REHM. Understanding the build-up of a technological innovation system around hydrogen and fuel cell technologies. *Int J Hydrogen Energy* 2009;34(24):9639–54.
- [43] Schönauer A-L, Glanz S. Hydrogen in future energy systems: social acceptance of the technology and its large-scale infrastructure. *Int J Hydrogen Energy* 2022;47(24):12251–63.

- [44] Iribarren D, et al. Assessing the social acceptance of hydrogen for transportation in Spain: an unintentional focus on target population for a potential hydrogen economy. *Int J Hydrogen Energy* 2016;41(10):5203–8.
- [45] UNIDO. Rebooting quality infrastructure for a sustainable future. 2020. Available from: [https://hub.unido.org/sites/default/files/publications/QI\\_SDG\\_PUBLICATION\\_Dec2019.pdf?\\_ga=2.258352010.1068267657.1673342869-1677971602.1673342869](https://hub.unido.org/sites/default/files/publications/QI_SDG_PUBLICATION_Dec2019.pdf?_ga=2.258352010.1068267657.1673342869-1677971602.1673342869).
- [46] Koch C, et al. Impact of the COVID-19 pandemic on accredited conformity assessment bodies: insights from a multinational study. *Accred Qual Assur* 2022;27:275–88. 28.
- [47] Mirtsch M, et al. Quality assurance in supply chains during the COVID-19 pandemic: empirical evidence on organisational resilience of conformity assessment bodies. *Total Qual Manag Bus Excel* 2022;34(5–6):1–22.
- [48] Blind K. In: Delimatsis P, editor. *From Standards to Quality Infrastructure. The law, economics and politics of international standardisation*. Cambridge: Cambridge University Press; 2015. p. 58–76.
- [49] Blind K, Mangelsdorf A, Pohlisch J. The effects of cooperation in accreditation on international trade: empirical evidence on ISO 9000 certifications. *Int J Prod Econ* 2018;198:50–9.
- [50] Gonçalves J, Peuckert J. *Measuring the impacts of quality infrastructure. Impact theory, empirics and study design*. Braunschweig: PTB; 2011.
- [51] Baumann M, et al. Comparative patent analysis for the identification of global research trends for the case of battery storage, hydrogen and bioenergy. *Technol Forecast Soc Change* 2021;165:120505.
- [52] Bundesministerium für Wirtschaft und Klimaschutz. *Fortschreibung der Nationalen Wasserstoffstrategie*. 2023. Berlin. Available from: [https://www.bmbf.de/SharedDocs/Downloads/de/2023/230726-fortschreibung-nws.pdf?\\_\\_blob=publicationFile&v=1](https://www.bmbf.de/SharedDocs/Downloads/de/2023/230726-fortschreibung-nws.pdf?__blob=publicationFile&v=1).
- [53] Adams WC. Conducting semi-structured interviews. In: Wholey J, Hatry H, Newcomer K, editors. *Handbook of practical program evaluation*. 4<sup>th</sup> ed. Wiley Online Library; 2015. p. 492–505.
- [54] Bryson J. What to do when stakeholders matter. *Publ Manag Rev* 2004;6(1):21–53.
- [55] Microsoft Co.. *Microsoft Teams*. 2022. Redmond.
- [56] Verbi Software. *MAXQDA*. 2022. Berlin.
- [57] Strauss A, Corbin J. *Basics of qualitative research: techniques and procedures for developing grounded theory*. Thousand Oaks, CA: Sage Publications, Inc; 1998.
- [58] Hardman S, et al. Barriers to the adoption of fuel cell vehicles: a qualitative investigation into early adopters attitudes. *Transport Res Pol Pract* 2017;95:166–82.
- [59] Eisenhardt KM, Graebner ME. Theory building from cases: opportunities and challenges. *Acad Manag J* 2007;50(1):25–32.
- [60] Weiss D. *Technological Innovation Systems: a critical review of quantitative methods*. In: Paper presented at the EU-SPRI 2022 conference; 2022.
- [61] Westphal K, Dröge S, Geden O. The international dimensions of Germany's hydrogen policy. *SWP Comment*; 32/2020. p. 2020.
- [62] Zimmer R, Welke J. Let's go green with hydrogen! The general public's perspective. *Int J Hydrogen Energy* 2012;37(22):17502–8.
- [63] Forschungsnetzwerke Energie. *Forschungsnetzwerk Wasserstoff*. 2023. Available from: <https://www.forschungsnetzwerke-energie.de/wasserstoff>.
- [64] Belova A, et al. The more the merrier? Actors and ideas in the evolution of German hydrogen policy discourse. *Energy Res Social Sci* 2023;97:102965.
- [65] Trencher G, Edianto A. Drivers and barriers to the adoption of fuel cell passenger vehicles and buses in Germany. *Energies* 2021;14(4):833.
- [66] Sadik-Zada ER, et al. Pathways to the hydrogen mobility futures in German public transportation: a scenario analysis. *Renew Energy* 2023;205:384–92.
- [67] Projektträger Jülich. *National innovation programme hydrogen and fuel cell technology (NIP)*. 2023. Available from: <https://www.ptj.de/en/project-funding/nip>.
- [68] NOW GmbH. *Wasserstoff und Brennstoffzelle*. 2023. Available from: <https://www.now-gmbh.de/foerderung/foerderprogramme/wasserstoff-und-brennstoffzelle/>.
- [69] European Commission. *IPCEI: EU Commission gives the green light to promote hydrogen technology — also in Germany*. 2022. Available from: [https://germany-representation.ec.europa.eu/news/ipcei-eu-kommission-gibt-grunes-licht-zur-forderung-von-wasserstofftechnologie-auch-deutschland-2022-07-15\\_de?etrans=en](https://germany-representation.ec.europa.eu/news/ipcei-eu-kommission-gibt-grunes-licht-zur-forderung-von-wasserstofftechnologie-auch-deutschland-2022-07-15_de?etrans=en).
- [70] Bundesministerium für Digitales und Verkehr. *BMDV fördert öffentliche Wasserstofftankstellen für Nutzfahrzeuge*. 2021. Available from: <https://bmdv.bund.de/SharedDocs/DE/Artikel/G/foerderung-oeffentliche-wasserstofftankstellen-nutzfahrzeuge.html>.
- [71] Acatech and Dechema. *Electrolysis in Germany: power, political goals and projected demand for 2030*. 2022. Available from: [https://www.wasserstoff-kompass.de/fileadmin/user\\_upload/img/news-und-media/dokumente/electrolysis\\_in\\_Germany\\_2030\\_01.pdf](https://www.wasserstoff-kompass.de/fileadmin/user_upload/img/news-und-media/dokumente/electrolysis_in_Germany_2030_01.pdf).
- [72] Wappler M, et al. Building the green hydrogen market — current state and outlook on green hydrogen demand and electrolyzer manufacturing. *Int J Hydrogen Energy* 2022;47(79):33551–70.
- [73] European Commission. *A hydrogen strategy for a climate-neutral Europe*. 2020. Brussels. Available from: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301>.
- [74] Lux B, et al. The role of hydrogen in a greenhouse gas-neutral energy supply system in Germany. *Energy Convers Manag* 2022;270:116188.
- [75] Federal Government of Germany. *Climate change act 2021*. Berlin: Intergenerational contract for the climate; 2021. Available from: <https://www.bundesregierung.de/breg-de/themen/klimaschutz/climate-change-act-2021-1936846>.
- [76] Deutscher Bundestag. *Gesetz zur Änderung des Energiewirtschaftsrechts gebilligt*. 2022. Berlin. Available from: <https://www.bundestag.de/dokumente/textarchiv/2022/kw25-de-energiewirtschaftsrecht-899952>.
- [77] Federal government of Germany. *Koalitionsvertrag zwischen SPD, Bündnis 90/Die Grünen und FDP*. 2021. Berlin.
- [78] Lavrijssen S, Vitéz B. Make hydrogen whilst the sun shines: how to turn the current momentum into a well-functioning hydrogen market? *Carbon & Climate Law Review* 2020;14(4):266–80.
- [79] Ringsgwandl LM, et al. Current legislative framework for green hydrogen production by electrolysis plants in Germany. *Energies* 2022;15(5):1786.
- [80] European Commission. *Commission delegated regulation (EU) of 10.2.2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin*. 2023. Brussels.
- [81] Council of the European Union. *Council and Parliament reach provisional deal on renewable energy directive*. 2023. Available from: <https://www.consilium.europa.eu/en/press/>

- press-releases/2023/03/30/council-and-parliament-reach-provisional-deal-on-renewable-energy-directive/.
- [82] Bundesministerium für Wirtschaft und Klimaschutz. Reallabore der Energiewende. 2022. Available from: <https://www.energieforschung.de/spotlights/reallabore>.
- [83] Ikonnikova SA, Scanlon BR, Berdysheva SA. A global energy system perspective on hydrogen Trade: a framework for the market color and the size analysis. *Appl Energy* 2023;330:120267.
- [84] Eicke L, De Blasio N. Green hydrogen value chains in the industrial sector—geopolitical and market implications. *Energy Res Social Sci* 2022;93:102847.
- [85] Bundesministerium für Bildung und Forschung. Grüner Wasserstoff: Welche internationalen Projekte fördert das BMBF?. 2023. Available from: <https://www.bmbf.de/bmbf/shareddocs/kurzmeldungen/de/woher-soll-der-gruene-wasserstoff-kommen.html>.
- [86] Forschungszentrum Jülich. H2 ATLAS-AFRICA. 2023. Available from: <https://www.h2atlas.de/en/>.
- [87] H2Global Foundation. New German government gives the go-ahead for the H2Global initiative. 2021. Available from: <https://www.h2-global.de/post/neue-bundesregierung-gibt-startschuss-fuer-h2global-initiative>.
- [88] Linnemann M, Peltzer J. (Wasserstoff-)Netze & regulierung In: Linnemann M, Peltzer J, editors. *Wasserstoffwirtschaft kompakt: Klimaschutz, Regulatorik und Perspektiven für die Energiewirtschaft*. Wiesbaden: Springer Fachmedien; 2022. p. 123–83.
- [89] Bernard MR. Policy update: European union alternative infrastructure regulation (AFIR). 2023. Available from: <https://theicct.org/publication/afir-eu-april2023/>.
- [90] Hypos East Germany. Wasserstoffnetzwerk; 2023. Available from: <https://www.hypos-eastgermany.de/wasserstoffnetzwerk/kompetenzen/>.
- [91] H2Mobility. Our H2 stations. 2023. Available from: <https://h2-mobility.de/unsere-tankstellen/>.
- [92] Quadflieg H. From research to market application? experience with the German hydrogen fuel project. *Int J Hydrogen Energy* 1988;13(6):363–74.
- [93] GASAG. Unsere Geschichte: Mehr als 175 Jahre Tradition aus Berlin. 2023. Available from: <https://www.gasag-gruppe.de/ueber-uns/organisation/geschichte-gasag>.
- [94] Weger LB, Leitão J, Lawrence MG. Expected impacts on greenhouse gas and air pollutant emissions due to a possible transition towards a hydrogen economy in German road transport. *Int J Hydrogen Energy* 2021;46(7):5875–90.
- [95] European Union. Directive 2014/68/EU of the European Parliament and of the Council of 15 May 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment. 2014. Brussels.
- [96] European Union. Directive 2014/34/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres. 2014. Brussels.
- [97] European Union. Commission communication in the framework of the implementation of Directive 2014/34/EU of the European Parliament and of the Council on the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres (Publication of titles and references of harmonised standards under Union harmonisation legislation). 2014. Brussels.
- [98] Sanetra C, Marbán RM. The answer to the global quality challenge: a national quality infrastructure. Braunschweig: Physikalisch-Technische Bundesanstalt; 2007.
- [99] Aswal DK. Quality infrastructure of India and its importance for inclusive national growth. *MAPAN* 2020;35(2):139–50.
- [100] Shen J, et al. Coupling relationship analysis between quality infrastructure and ecological environment quality for policy implications. *Int J Environ Res Publ Health* 2020;17(20):7611.
- [101] DIN. Normungsroadmap wasserstofftechnologien. 2023. Available from: <https://www.din.de/de/forschung-und-innovation/themen/wasserstoff/normungsroadmap-wasserstoff>.
- [102] CertifHy Consortium. What is CertifHy?. 2022. Available from, <https://www.certifhy.eu/>.
- [103] Velazquez Abad A. Green hydrogen characterisation initiatives: definitions, standards, guarantees of origin, and challenges. *Energy Pol* 2020;138:111300.
- [104] Ball M, Wietschel M. The future of hydrogen – opportunities and challenges. *Int J Hydrogen Energy* 2009;34(2):615–27.
- [105] Emodi NV, et al. A systematic literature review of societal acceptance and stakeholders' perception of hydrogen technologies. *Int J Hydrogen Energy* 2021;46(60):30669–97.
- [106] Gordon JA, Balta-Ozkan N, Nabavi SA. Homes of the future: unpacking public perceptions to power the domestic hydrogen transition. *Renew Sustain Energy Rev* 2022;164:112481.
- [107] Baur D, et al. Assessing the social acceptance of key technologies for the German energy transition. *Energy, Sustainability and Society* 2022;12:4.
- [108] Huijts NMA, Molin EJE, Steg L. Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework. *Renew Sustain Energy Rev* 2012;16(1):525–31.
- [109] Hienuki S, et al. How knowledge about or experience with hydrogen fueling stations improves their public acceptance. *Sustainability* 2019;11(22):6339.
- [110] Bentsen HL, et al. In the green? Perceptions of hydrogen production methods among the Norwegian public. *Energy Res Social Sci* 2023;97:102985.
- [111] Scovell MD. Explaining hydrogen energy technology acceptance: a critical review. *Int J Hydrogen Energy* 2022;47(19):10441–59.
- [112] Noailly J, Shestalova V. Knowledge spillovers from renewable energy technologies: lessons from patent citations. *Environ Innov Soc Transit* 2017;22:1–14.
- [113] Hu G, et al. A review of technical advances, barriers, and solutions in the power to hydrogen (P2H) roadmap. *Engineering* 2020;6(12):1364–80.
- [114] Shiva Kumar S, Lim H. An overview of water electrolysis technologies for green hydrogen production. *Energy Rep* 2022;8:13793–813.
- [115] Neuwirth M, et al. The future potential hydrogen demand in energy-intensive industries - a site-specific approach applied to Germany. *Energy Convers Manag* 2022;252:115052.
- [116] Yukesh Kannah R, et al. Techno-economic assessment of various hydrogen production methods – a review. *Bioresour Technol* 2021;319:124175.
- [117] Kothari R, Buddhi D, Sawhney RL. Comparison of environmental and economic aspects of various hydrogen production methods. *Renew Sustain Energy Rev* 2008;12(2):553–63.
- [118] Aziz M. Liquid hydrogen: a review on liquefaction, storage, transportation, and safety. *Energies* 2021;14(18):5917.
- [119] Alves MP, et al. A review on industrial perspectives and challenges on material, manufacturing, design and development of compressed hydrogen storage tanks for the transportation sector. *Energies* 2022;15(14):5152.
- [120] Paster MD, et al. Hydrogen storage technology options for fuel cell vehicles: well-to-wheel costs, energy efficiencies,



- and greenhouse gas emissions. *Int J Hydrogen Energy* 2011;36(22):14534–51.
- [121] Watts RJ, Porter AL. Innovation forecasting. *Technol Forecast Soc Change* 1997;56(1):25–47.
- [122] Blind K, Filipović E, Lazina L. Motives to publish, to patent and to standardize: an explorative study based on individual engineers' assessments. *Technol Forecast Soc Change* 2022;175:121420.
- [123] Blind K, Pohlisch J, Zi A. Publishing, patenting, and standardization: motives and barriers of scientists. *Res Pol* 2018;47(7):1185–97.
- [124] Dziallas M, Blind K. Innovation indicators throughout the innovation process: an extensive literature analysis. *Technovation* 2019;80–81:3–29.
- [125] Cammeraat E, Dechezleprêtre A, Lalanne G. Innovation and industrial policies for green hydrogen. In: *OECD science, technology and industry policy papers*, No. 125. Paris: OECD Publishing; 2022.
- [126] Ueckerdt F, et al. Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nat Clim Change* 2021;11(5):384–93.
- [127] Yuan X, Cai Y. Forecasting the development trend of low emission vehicle technologies: based on patent data. *Technol Forecast Soc Change* 2021;166:120651.
- [128] European Commission. Questions and answers on the REPowerEU communication. 2022. Available from: [https://ec.europa.eu/commission/presscorner/detail/en/qanda\\_22\\_3132](https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_3132).
- [129] H2KOREA. Introduction of H2KOREA and strategy for implementing the Korean Hydrogen Economy. 2022. Seoul.
- [130] Park S. The country-dependent shaping of 'hydrogen niche' formation: a comparative case study of the UK and South Korea from the innovation system perspective. *Int J Hydrogen Energy* 2013;38(16):6557–68.
- [131] Yoo S, Park S. South Korea's national pursuit for fuel cell electric vehicle development: the role of government R&D programs over 30 years (1989–2021). *Int J Hydrogen Energy* 2023;48(26):9540–50.
- [132] Wang Y, et al. Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology. *Energy and AI* 2020;1:100014.
- [133] Shin J-E. Hydrogen technology development and policy status by value chain in South Korea. *Energies* 2022;15(23):8983.
- [134] Ministry of Trade, Industry and Energy. Government announces new policies to boost hydrogen industry. 2022. Available from: [http://english.motie.go.kr/en/pc/pressreleases/bbs/bbsView.do?bbs\\_cd\\_n=2&bbs\\_seq\\_n=1120](http://english.motie.go.kr/en/pc/pressreleases/bbs/bbsView.do?bbs_cd_n=2&bbs_seq_n=1120).
- [135] Youngok K, Eunkyung Y, Hyunik S. Russia's policy transition to a hydrogen economy and the implications of South Korea–Russia cooperation. *Energies* 2021;15(1):127.
- [136] Hong S, Kim E, Jeong S. Evaluating the sustainability of the hydrogen economy using multi-criteria decision-making analysis in Korea. *Renew Energy* 2023;204:485–92.
- [137] Beckstedde E, et al. Regulatory sandboxes: do they speed up innovation in energy? *Energy Pol* 2023;180:113656.
- [138] GHIAA. Global Hydrogen industrial association alliance. 2022. Available from, <http://www.ghiaa.net/eng/brand/intro>.
- [139] Blind K, Jungmittag A. Trade and the impact of innovations and standards: the case of Germany and the UK. *Appl Econ* 2005;37(12):1385–98.
- [140] Swann P. International standards and trade: a review of the empirical literature. In: *OECD trade policy papers*, No. 97. Paris: OECD Publishing; 2010.
- [141] Kang H-S, Kim S-M, Kim J. Safety issues of a hydrogen refueling station and a prediction for an overpressure reduction by a barrier using OpenFOAM software for an SRI explosion test in an open space. *Energies* 2022;15(20):7556.
- [142] Kang MJ, Park H. Impact of experience on government policy toward acceptance of hydrogen fuel cell vehicles in Korea. *Energy Pol* 2011;39(6):3465–75.
- [143] Schulte I. Issues affecting the acceptance of hydrogen fuel. *Int J Hydrogen Energy* 2004;29(7):677–85.
- [144] Wang Y, et al. An empirical study of consumers' intention to use ride-sharing services: using an extended technology acceptance model. *Transportation* 2020;47(1):397–415.
- [145] Lee Y, et al. Evaluating hydrogen risk management policy PR: lessons learned from three hydrogen accidents in South Korea. *Int J Hydrogen Energy* 2023;48(63):24536–47.
- [146] Han S-M, Kim J-H, Yoo S-H. The public's acceptance toward building a hydrogen fueling station near their residences: the case of South Korea. *Int J Hydrogen Energy* 2022;47(7):4284–93.
- [147] E4tech. Fuel cell industry review 2021. 2022. Available from: <https://www.e4tech.com/resources/249-fuel-cell-industry-review-2021.php>.
- [148] Losacker S, Liefner I. Regional lead markets for environmental innovation. *Environ Innov Soc Transit* 2020;37:120–39.
- [149] Quitzow R, et al. The concept of "lead markets" revisited: contribution to environmental innovation theory. *Environ Innov Soc Transit* 2014;10:4–19.
- [150] Blind K, Fenton A. Standard-relevant publications: evidence, processes and influencing factors. *Scientometrics* 2022;127:577–602.
- [151] Lee E, Mah JS. Industrial policy and the development of the electric vehicles industry: the case of Korea. *J Technol Manag Innovat* 2020;15(4):71–80.
- [152] IEA. Global EV Outlook. 2022. p. 2022. Available from: <https://www.iea.org/reports/global-ev-outlook-2022>.
- [153] Ritchie H, Roser M. South Korea: Energy country profile. *Our World in Data*. 2022.
- [154] Acemoglu D, et al. Transition to clean technology. *J Polit Econ* 2016;124(1):52–104. <https://doi.org/10.1086/684511>.
- [155] Cervantes M, et al. Driving low-carbon innovations for climate neutrality. In: *OECD science, technology and industry policy papers*, No. 143. Paris: OECD Publishing; 2023.
- [156] Anderson B, et al. Designing policy packages for a climate-neutral industry: a case study from The Netherlands. *Ecol Econ* 2023;205:107720.
- [157] QI-Digital. Reliable hydrogen refueling stations. 2023. Available from: <https://www.qi-digital.de/en/reliable-hydrogen-filling-station>.
- [158] Falcone PM, Morone P, Sica E. Greening of the financial system and fuelling a sustainability transition: a discursive approach to assess landscape pressures on the Italian financial system. *Technol Forecast Soc Change* 2018;127:23–37.