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Knowledge and technology transfer via publications, patents, standards: Exploring the hydrogen technological innovation system

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ABSTRACT

Clean technologies play a crucial role in reducing greenhouse gas emissions and protecting the climate. Hydrogen is a promising energy carrier and fuel that can be used in many applications. We explore the global hydrogen technological innovation system (TIS) by analyzing the three knowledge and technology transfer channels of publications, patents, and standards. Since the adoption of hydrogen technologies requires trust in their safety, this study specifically also focuses on hydrogen safety. Our results show that general and hydrogen safety research has increased significantly while patenting experienced stagnation. An analysis of the non-patent literature in safety patents shows little recognition of scientific publications. Similarly, publications are underrepresented in the analyzed 75 international hydrogen and fuel cell standards. This limited transfer of knowledge from published research to standards points to the necessity for greater involvement of researchers in standardization. We further derive implications for the hydrogen TIS and recommendations for a better and more impactful alignment of the three transfer channels.

1. Introduction

The response to global climate challenges and securing future energy supplies require new approaches. Alternative, sustainable energy sources and fuels are receiving increasing attention (Ambrose et al., 2017; Andwari et al., 2017; Blanco et al., 2018; Romejko and Nakano, 2017). They play a crucial role in reducing emissions in the residential, traffic and transportation, and industrial sectors, which use fossil fuels primarily (Al-Amin and Doberstein, 2019; Sarkar et al., 2019). Cleaner alternative technologies are necessary against the backdrop of sustainable development (Al-Amin and Doberstein, 2019; Sarkar et al., 2019). In this context, hydrogen technologies are a promising approach that has received considerable political attention in recent years. Since hydrogen combustion does not produce direct emissions that could be harmful to the climate (Albrecht et al., 2020; Veziroglu, 2007), it has the potential to become a climate-friendly alternative. However, hydrogen must be made from renewable energies[1] to be a clean energy source (Abdel-Wahab and Ali, 2013; Acar and Dincer, 2015). Despite "green" production, hydrogen storage is still inefficient and unsustainable. Hydrogen must be stored at extremely low temperatures and high pressure that require much energy (Edwards et al., 2007). Although the technology is not yet sufficiently effective, it has great potential for the future.

Hydrogen has been the subject of extensive R&D efforts aimed at promoting innovation in that area (Behling, 2013) and is supported by ambitious national hydrogen strategies worldwide (Albrecht et al., 2020). R&D as a pillar of innovation is disseminated through knowledge and technology transfer channels in the form of publications, patents, and standards (OECD and Eurostat, 2018). These channels pave the way from research to market introduction. However, new technologies must be safe to gain society's trust and enter the market (Linke, 2009; Turinsky and Kothe, 2016; Weiner et al., 2013).

We operationalize the knowledge flows within the hydrogen technological innovation system (TIS) using publications, patents, and standards as indicators. For this purpose, we conduct bibliometric analyses of the three channels. Existing bibliometric publication analyses on hydrogen technologies find steady growth in research volume (Chanchetti et al., 2020; He et al., 2019; Tsay, 2008). In contrast, analyses of hydrogen patents detect divergent patterns in patenting trends (Bakker,

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[1] Also referred to as "green" hydrogen.

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2010a,b; Sinigaglia et al., 2019). Other studies looking at the intersection of hydrogen publications and patents find increased convergence between both channels (Huang et al., 2015). Ultimately, the third channel, standards, has been largely neglected in bibliometric studies of hydrogen technologies.

By comprehensively referring to the three knowledge and technology transfer channels - with a particular focus on hydrogen safety - we contribute to hydrogen-economy research at several levels. For the first time, we analyze hydrogen publications, patents, and standards as TIS indicators and their interplay, in particular, what is, to our knowledge, the first empirical analysis of hydrogen standards. With this, we explore developments and interrelations in the hydrogen TIS and shed light on the heterogeneous results of bibliometric hydrogen publication and patent analyses in other studies. Furthermore, we demonstrate the importance of hydrogen safety and intensified interplay between the three knowledge and technology transfer domains for a more developed hydrogen TIS, including more rapid technology diffusion.

The remainder of this paper is structured as follows: In Section 2, we present the conceptual background of this paper. Section 3 introduces the methodology: bibliometric analyses of hydrogen publications, patents, and standards. In Section 4, we present the results of our study, which we then discuss (Section 5). The final section summarizes our main findings and addresses some limitations. Finally, we further suggest future research priorities.

2. Conceptual background

2.1. Hydrogen economy and the role of safety

The hydrogen economy describes the large-scale deployment of hydrogen in various sectors. It aims at 1.) increasing energy supply, 2.) reducing energy costs, 3.) fulfilling all functions of common energy media, and consists of several elements (Bockris, 2013; Bockris and Appleby, 1972): Hydrogen production, storage, transportation, and applications, such as in hydrogen refueling station infrastructures or fuel cell vehicles (Mazloomi and Gomes, 2012; Najjar, 2013; Sinigaglia et al., 2019).

For its potential to be used in sectors dominated by fossil fuels (Dodds et al., 2015; Umweltbundesamt, 2020), the hydrogen economy contributes to the energy transition toward more sustainable energy carriers and fuels[2] (Al-Amin and Doberstein, 2019; Sarkar et al., 2019). Furthermore, it can secure energy supplies in the future (Andwari et al., 2017; Ball and Wietschel, 2009; Romejko and Nakano, 2017). However, fossil energy is still the dominant energy carrier due to the lack of cost-effective, sustainable alternatives.

For instance, hydrogen energy production still involves high costs, a lack of technological performance (especially in hydrogen storage and transportation), and available infrastructure (Andrews and Shabani, 2014).

Among the barriers to the diffusion of hydrogen technologies, safety is one of the critical concerns. Solving technological issues related to hydrogen technologies will considerably enhance their safety (Ambrose et al., 2017; Fowler et al., 2016). Sufficient levels of safety and trust in the technologies' safety thus create public acceptance. This, in turn, facilitates the market entry of hydrogen technologies (Aprea, 2008; Ball and Wietschel, 2009; Dutta, 2014; Hardman et al., 2017; Kikukawa et al., 2009; Markert et al., 2007; Schulte, 2004). For instance, raising public awareness of hydrogen safety can increase trust in hydrogen and pave the way for its widespread market introduction (Besley and Baxter-Clemmons, 2010; Hardman et al., 2017; Schulte, 2004).

Due to the fundamental role of safety in the adoption of hydrogen technologies, we consider publications and patent applications with a general focus on hydrogen and those more specialized in hydrogen safety. In addition, we consider international hydrogen and fuel cell standards.

2.2. The life cycle of technological innovations systems

As a conceptual framework of analysis, we apply a Technological Innovation System (TIS) approach, which helps explain the "emergence and development of new technologies" (Markard, 2020). Bergek et al. (2015) define a TIS as "a set of elements, including technologies, actors, networks and institutions, which actively contribute to the development of a particular technology field". The TIS elements are defined as follows (Bergek et al., 2015; Markard, 2020): Actors and networks include manufacturers, suppliers, research institutions, or networks thereof. Institutions in a TIS are referred to as formal structures, while technology, as the third component of the TIS, refers to the direction of technology development and technology variation. According to Markard et al. (2020), various empirical indicators can be used to represent the TIS dimensions. Among others, these include publications and patents as indicators of the actor base, and standards as an indicator of the institutional structure of the TIS, while all three channels also shape the third element of the TIS, technology. Furthermore, the use of publications, patents, and standards as empirical TIS indicators is justified by their importance as three knowledge and technology transfer channels in R&D (Blind and Fenton, 2022; Blind et al., 2018, 2022a), which disseminate research and innovation (Watts and Porter, 1997; OECD and Eurostat, 2018). However, previous empirical TIS research mainly uses qualitative approaches that hardly permit to quantify the actors, institutions, and technology dimensions of the TIS (Ko et al., 2021; Konrad et al., 2012; Markard et al., 2020). Based on the analysis of the elements of the hydrogen TIS, we apply the TIS life cycle approach by Markard et al. (2020) that captures the dynamics of emerging technologies' TISs. With this, we aim to assess the life cycle phase of the hydrogen TIS. The TIS life cycle consists of four phases: the formative phase ('nascent TIS'), the growth phase ('expanding TIS'), the maturity phase ('mature TIS'), and the decline phase ('declining TIS') (Markard, 2020; Markard et al., 2020). Fig. 1 illustrates the TIS life cycle framework with its three key dimensions: 1.) the core components, 2.) the analytical dimensions, and 3.) the transformational perspective.

The core components comprise the TIS itself and its context, e.g., competing TISs. The analytical dimensions of the TIS are the actors, institutions and networks, and technology. Finally, the transformational perspective comprises parameters to operationalize the development of the TIS life cycle. These include, for instance, the expansion, decline, or institutionalization of the TIS (Markard, 2020).

In the area of hydrogen-related TIS research, Suurs et al. (2009) used the TIS approach to explore the development of the hydrogen and fuel cell innovation system in the Netherlands. The authors identified the key drivers and barriers to the emergence of hydrogen innovation systems.

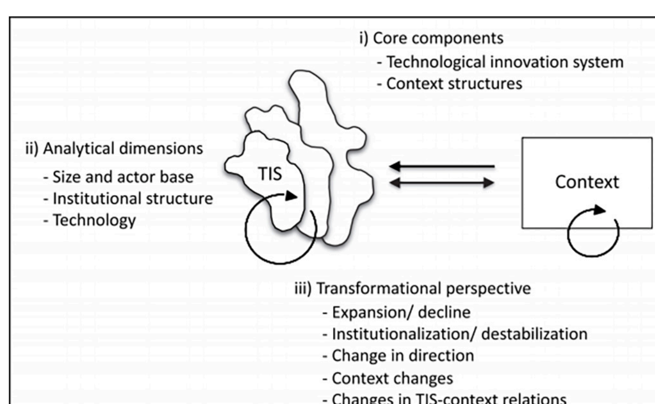

Fig. 1. TIS Framework, retrieved from Markard et al. (2020).

[2] Note: if produced by renewable energies.

However, the authors did not investigate the TIS life cycle. Hacking et al. (2019) investigated the UK hydrogen and fuel cell innovation system from 1954 to 2012 based on event history analysis and expert interviews. The results show evidence of the impact of different types of investments and locations on the development of the hydrogen TIS. However, the authors do not refer to publications, patents, and standards to evaluate the TIS.

Given the addressed research gaps, this study contributes to empirical and theoretical TIS research: First, this study is the first attempt to analyze a TIS using publications, patents, and standards as empirical, quantitative TIS indicators. Second, we contribute to theoretical TIS research by demonstrating that publications, patents, and standards should be more explicitly included in TIS frameworks as a way of better operationalizing a TIS. Third, we demonstrate that our TIS indicators are adequate for assessing the life cycle phase and maturity of a TIS.

2.3. Bibliometric evidence on hydrogen technologies and research questions

Bibliometric analyses of hydrogen technologies have focused on single elements of the hydrogen economy (see Section 2.1). However, Tsay's (2008) study of hydrogen energy publications traces the evolution of hydrogen research regardless of the hydrogen value chain. It shows that the number of hydrogen publications grew exponentially in the 1965–2005 period. Furthermore, the analysis breaks down the results by document types, languages, countries, institutions, and most influential journals.

Other bibliometric studies focus on specific aspects of the hydrogen economy. For instance, Zhao et al. (2020) bibliometrically analyze the literature on microbial electrolysis cells (MECs) for hydrogen production to identify and compare different MEC configurations. In their studies on hydrogen storage, Chanchetti et al. (2020) and He et al. (2019) analyzed the hydrogen storage literature bibliometrically. Except for the declining trend after 2014 in He et al. (2019), both studies find a steady growth of research in their respective study periods. The findings point to the increased attention attached to hydrogen storage research.

Regarding hydrogen applications, Suominen (2014) finds that fuel cell research increased steadily from 1991 to 2010. Furthermore, the author explores that transnational fuel cell research networks expanded in that period, pointing to increased research activity. In contrast, the proton exchange membrane (PEM) fuel cell research analysis by Yonoff et al. (2019) shows less pronounced growth between 2008 and 2018. The review of bibliometric publication analyses demonstrates that more specialized bibliometric hydrogen analyses generally show less clear trends. Therefore, hydrogen publication analyses differ in terms of their main findings, especially for single elements of the hydrogen economy.

Using publications as an indicator of science and patents as an indicator of technology, Huang et al. (2015) address the intersection of hydrogen publication and patent analysis. The authors find that publications and patents are increasingly converging in the fuel cell field. Furthermore, they identify research institutions as strengthening the linkages between other institutions' publications and patents. In an extensive study on hydrogen patents, Chen et al. (2011) created a four-stage logistic growth curve model of technology development that comparatively analyzed the maturity of hydrogen generation, storage, and fuel cell technology based on patent application data. Subsequently, the authors determined the maturity of each of the technologies.

Sinigaglia et al. (2019) explore the evolution of patent growth between 1998 and 2018, finding a sharp decline in patent growth from 2012 onwards. In addition, the authors provide a detailed overview of the different actors involved in hydrogen patenting. Specializing in hydrogen production, Hsu et al. (2014) analyze patents on biomass and wastewater hydrogen production. The authors classify the patents according to the materials designated, the technologies applied, and their functions in hydrogen production. In the area of fuel cells, Bakker (2010a,b) compares patents on different onboard hydrogen storage and conversion technologies to assess their degree of commercialization. While patents on hydrogen conversion converged toward PEM fuel cells, patents on hydrogen storage diverged from each other. The author concludes that storage technologies have failed to become commercialized (Bakker, 2010a,b).

Hydrogen standards as the third channel of knowledge and technology transfer have not been the subject of empirical studies. However, standardization and standards considerably enhance hydrogen safety (Aprea, 2008, 2014), facilitating hydrogen technology diffusion (Cairns, 2010). For example, Dincer and Acar (2017) point to the vital role of standardization in enhancing hydrogen safety, scaling up hydrogen production, and developing the infrastructure for commercialization. In the same vein, Wurster and Hof (2020) emphasize the importance of regulations, codes, and standards (RCS) for the market introduction of hydrogen technologies on a global scale, especially internationally harmonized and interoperable standards.

This research is the first attempt to analyze the global hydrogen TIS, including the consideration of hydrogen safety, by means of the three knowledge and technology transfer channels of publications, patents, and standards (Blind and Fenton, 2022; Blind and Gauch, 2009; Blind et al., 2018, 2022a; Dziallas and Blind, 2019; Zi and Blind, 2015). To this end, we conduct a bibliometric analysis of publications, patents, and standards, and investigate their interplay to assess the knowledge flows and the life cycle stage of the hydrogen TIS (Chen et al., 2011; Garfield et al., 1978).

We complement existing research on TIS and publications, patents, and standards with hydrogen as a relevant application field in addressing the following research questions:

RQ1: What are the patterns in the development of science and technology related to hydrogen technologies and hydrogen safety technologies in particular?

RQ2: How are the knowledge and technology transfer channels linked in hydrogen technologies and hydrogen safety technologies in particular?

RQ3: What do the patterns in publications, patents, and standards imply about the life cycle of the global hydrogen TIS?

3. Methodology

3.1. Publication analysis

Bibliometric publication analysis is a method to quantitatively analyze a large pool of scientific documents. These include, e.g., research papers or conference proceedings. This method mitigates selection bias in analyzing existing research (van Oorschot et al., 2018; Vogel and Güttel, 2012). In addition, patterns and trends in research and technological advances can be identified (Watts and Porter, 1997) by measuring the number of publications and their contents (Chen et al., 2011; Norton, 2000).

This paper comparatively and quantitatively analyzes the literature on hydrogen technologies in general and those with a particular focus on safety. To this end, we conduct descriptive data analyses and replicate the levels of analysis of He et al. (2019) and Tsay (2008). Thus, we present the countries, institutions, and research areas most active in general hydrogen and hydrogen safety research and the total number of publications per year.

3.2. Patent analysis

Bibliometrics is also applicable for analyzing developments in patenting (Abbas et al., 2014; Watts and Porter, 1997). It allows for exploring trends in hydrogen technology development (Chang et al., 2010; Narin, 1994). In this paper, we examine and compare patent application data on hydrogen technologies in general and those with a safety focus. In this way, we compare our findings from safety patents with general hydrogen patents. Our data analysis uses descriptive statistics to identify the most active patent assignees and their home countries. We assess the hydrogen and hydrogen safety patenting stage by classifying patenting over time according to the life cycle stages of new technologies by Ernst (1997), who distinguishes the different stages of patenting: emerging, growth, maturity, and saturation (Chanchetti et al., 2016; Ernst, 1997). In addition, we focus on analyzing the non-patent literature (NPL) cited in the hydrogen safety patents in our sample. To this end, we collected hydrogen patent documents containing NPL. Then, we analyzed 22 of these non-patent references available in the Web of Science (WoS). Finally, we structured the NPL results by countries, institutions, and research areas.

3.3. Analysis of standard-relevant publications

A standard is a "formalized document defined by consensus and approved by a recognized body that provides, for common and repeated use, rules or guidelines for the characteristics of products, processes, and organizations" (Blind, 2004; OECD and Eurostat, 2018). Developed by interested stakeholders, standards emerge along various phases of the research and innovation process (Blind et al., 2018). Standards may list relevant scientific publications in their references as a disclosed scientific evidence base (Blind and Fenton, 2022). Similar to the bibliometric publication and patent analysis, we analyze the references of standards to identify knowledge and technology transfer (Blind and Fenton, 2022; Blind et al., 2018). Reference analysis aims to structure document references according to predefined criteria, such as research areas, document types, or the age of the referenced literature (Blind and Fenton, 2022; Chubin and Moitra, 1975; Glänzel and Schoepflin, 1999; Glänzel et al., 1999a; Glänzel et al., 1999b; Wainer et al., 2011). Moreover, reference analysis helps distinguish between scientific and non-scientific contributions to a given document (Blind and Fenton, 2022; Hou et al., 2011).

Although designed primarily to analyze scientific literature, we apply reference analysis to empirically investigate the references of international hydrogen and fuel cell standards. We thus trace the emergence of these standards by analyzing the types of references that shape them. We distinguish between normative references, i.e., cross-references to other standards, scientific references, and other references (e.g., regulations, directives). Among the reference types, we analyze the scientific references in standards in depth. We refer to these as standard-relevant publications (Blind and Fenton, 2022). We then break down these publications by the most frequently cited research areas and institutions, including their home countries.[3] This provides insights into the knowledge and technology transfer from publications to standards (Blind and Fenton, 2022). Subsequently, we validate our findings on the analysis of standard-relevant publications against the results of the bibliometric publication analysis.

3.4. Data collection

We retrieved our publication data from Clarivate Analytics's Web of Science (WoS) Core Collection, representing the most comprehensive scientific publications database across various disciplines (Web of Science, 2021). To collect our data, we entered relevant search terms in the "Topic" field (searching by title, abstract, and keywords) of the WoS search for hydrogen and hydrogen safety publications.[4] Search results were restricted to English-language journal articles and proceedings to exclude document types and languages marginally represented in hydrogen research. The period studied ranges from 1980 to 2020.

To collect our patent data, we used the IPlytics platform (IPlytics, 2021), which provides a comprehensive collection of patents filed at major national, regional, and international patent offices. We focus on patent applications to avoid bias due to expired or pending patents. Further, we limited patent applications to those filed at the European Patent Office (EPO). Extending the search to further patent offices would yield more records. However, this is problematic because the procedures for patent applications differ significantly across the different patent offices and are hardly harmonized (Callaert et al., 2006; Choi and Park, 2018). For collecting general hydrogen patent data, we used the search terms "Hydrogen OR fuel cell" in the "Title" field. For hydrogen safety patents, we additionally used "safe* OR secur*" in the "Title/Abstract/Claims" field. We used these simple search terms to avoid bias in the results (Bakker, 2010a,b). The timespan ranges from 1980 to 2020.

To collect relevant international hydrogen and fuel cell standards, we first used all standards listed in the *Hydrogen/Fuel Cell Codes & Standards* database (FCHEA, 2021) published by the U.S. Fuel Cell and Hydrogen Energy Association (FCHEA). Subsequently, we identified the accordant International Classification of Standards (ICS) code for each standard and the publishing Technical Committee (TC). Finally, we complemented our initial list by identifying all remaining relevant standards published under the ICS codes and TCs of the standards in the FCHEA list. Altogether, the international hydrogen standards pertinent to this paper are released only by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). The reference data of the standards were retrieved from the ISO Online Browsing Platform (ISO, 2021) for ISO standards and the VDE Standards Library (VDE, 2021) for IEC standards. Finally, we collected all references in the reference sections of the standards and additional in-text normative references.

4. Results

4.1. Results of publication analysis

We retrieved a total of 158409 publications on general hydrogen research and 32189 publications on hydrogen safety research for the period 1980–2020. Fig. 2 captures the trend of relevant publications per year across all active researching countries. Overall, general hydrogen and hydrogen safety research rose steadily from 1980 to 2020. From 1980 to 1990, the level of research was negligible. Thereafter, general hydrogen publications increased consistently, as did hydrogen safety publications increasingly since the mid-2000s.

Both the country ranking (Table 1) and the ranking of research institutions (Table 2) show general correspondence, with China and the USA as the most important players by large. Most countries and institutions involved in general hydrogen research are also identified as influential players in hydrogen safety research. However, some countries are specialized in hydrogen safety research while not being top represented in general hydrogen research, e.g., Sweden (Table 1). As expected, all of the home countries of the top institutions (Table 2) are also represented in the top publishing countries (Table 1). Highly productive national research institutions thus accumulate high productivity for their home countries.

[3] Note: The countries refer to the authors' affiliation at the time of publication.

[4] Hydrogen safety: hydrogen*safety OR security; hydrogen energy*safety OR security; hydrogen technology*safety OR security; fuel cell*safety OR security; hydrogen*production OR generation OR storage OR transport OR delivery OR fueling station AND safety OR security; fuel cell*vehicles OR infrastructure AND safety OR security; hydrogen*incidents OR accidents; hydrogen*explosion OR combustion OR flammability OR embrittlement OR health risks.

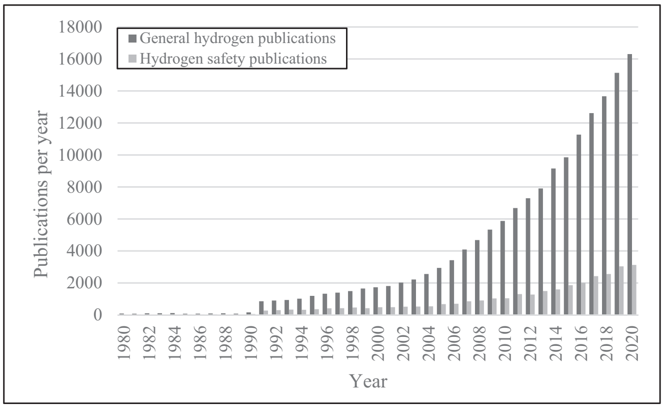

Fig. 2. Evolution of general hydrogen and hydrogen safety publications.

Table 1
General hydrogen and hydrogen safety publications by country.

General hydrogen research			Hydrogen safety research		
Rank	Country	Records, (%)	Rank	Country	Records, (%)
1	China	43491 (27.5)	1	USA	7118 (22.1)
2	USA	31157 (19.7)	2	China	6809 (21.2)
3	Japan	12853 (8.1)	3	Japan	2945 (9.5)
4	Germany	10042 (6.3)	4	Germany	2632 (8.2)
5	India	8241 (5.2)	5	UK	2144 (6.7)
6	UK	8223 (5.2)	6	France	1621 (5.0)
7	South Korea	8053 (5.1)	7	India	1530 (4.8)
8	France	7014 (4.4)	8	Russia	1528 (4.7)
9	Canada	5568 (3.5)	9	South Korea	1434 (4.5)
10	Italy	5552 (3.5)	10	Italy	1257 (3.9)
11	Spain	5203 (3.3)	11	Canada	1148 (3.6)
12	Australia	4345 (2.7)	12	Spain	979 (3.0)
13	Russia	4209 (2.7)	13	Australia	901 (2.8)
14	Iran	3618 (2.3)	14	Iran	654 (2.0)
15	Taiwan	3289 (2.1)	15	Taiwan	624 (1.9)
16	Netherlands	2843 (1.8)	16	Netherlands	576 (1.8)
17	Brazil	2590 (1.6)	17	Sweden	572 (1.8)
18	Poland	2502 (1.6)	18	Switzerland	494 (1.5)
19	Switzerland	2412 (1.5)	19	Poland	441 (1.4)
20	Turkey	2379 (1.5)	20	Brazil	411 (1.3)
	Total	158409 (100)		Total	32189 (100)

In terms of research areas of hydrogen publications, technical research areas dominate in both general and hydrogen safety research (Table 3). In contrast, social and economic sciences research is poorly represented and has received little attention. However, previous research has shown the importance of trust and social acceptance (Kikukawa et al., 2009) and favorable economic conditions, such as taxes, subsidies, and infrastructure investments, for hydrogen market development (Karger and Bongartz, 2008; Keles et al., 2008), which calls for intensified research in these areas.

4.2. Results of the patent analysis

We collected a total of 8936 general hydrogen patent applications spread across 161 classes of the International Patent Classification (IPC) and 342 hydrogen safety patents spread across 29 IPC classes.[5] Fig. 3 documents the evolution of patent applications between 1980 and 2020. Patent applications on general hydrogen technologies show an increase over the study period, with only a slight decline following the financial crisis in 2010 and a peak of 1206 in 2018. Only thereafter is a decline and stagnation observed, which requires further observations in terms of a sustained trend. Increasing international policy endeavors, such as national hydrogen strategies, might well reverse this development. However, the number of hydrogen safety patents remains consistently low, accounting for an average of only 2.7 % of all hydrogen patent applications.

To classify the development of hydrogen patenting, we relate our results to the patent-based technological S-curve in accordance with Ernst (1997). Ernst (1997) distinguishes the emerging, consolidation, and market penetration phases of patenting to determine a technology's technological life cycle. Despite some decreases in hydrogen patenting, the general trend is positive. This is a distinct characteristic of both the emerging and market-penetration phase. However, especially hydrogen safety patenting remains at a consistently low level. With this, we reject the findings by Chen et al. (2011) on the prediction of hydrogen patenting. The authors found that hydrogen production and storage technologies were in their growth stage at the time of their study. In contrast, we conclude from our results that, overall, hydrogen patenting is in its emerging phase.

Table 4 gives an overview of the 15 current assignees with the most patent applications. Japanese companies, especially car manufacturers, lead the ranking of general hydrogen patent filing with 7 companies, followed by German assignees (3). South Korean, French, U.S., and UK assignees complement the top list.

Looking at safety patents specifically, we observe that the players are different from those in general patenting. While Japanese and German organizations still represent the most active applicants, patents are also filed by other companies than in general hydrogen patents – and a French institute leads the list. Our findings are partially consistent with those of Bakker (2010a,b) and Sinigaglia et al. (2019), who both confirm the leading role of Japanese and South Korean companies in hydrogen patenting.

To capture the knowledge and technology transfer between publications and patents (Blind and Fenton, 2022; Blind et al., 2018, 2022a), we exemplarily ran a WoS analysis of non-patent literature (NPL) citations in the total of 342 hydrogen safety patents (see Tables A.1, A.2, Appendix A). 47 of these patent documents contain NPL. We analyzed the 22 non-patent citations of scientific publications available in the WoS from these patent documents.[6] We find that hydrogen safety patents predominantly cite publications from technical research areas, especially energy fuels, electrochemistry, and materials science. U.S. researchers are cited most frequently, followed by Japanese and German researchers. This also corresponds to the ranking of the most active patent assignees (Table 4) and countries in hydrogen safety research (Table 1).

4.3. Results of the standard analysis

We collected 50 ISO and 25 IEC hydrogen and fuel cell standards to gain insights into the different reference categories that shape the standards. All the gathered standards are distributed across 10 classes of the International Classification for Standards (ICS) and were released by five different ISO and four IEC technical committees (TCs). In these standards, we found a total of 1840 references. Table 5 shows the total number of relevant standards and the number of references per standardization organization. Furthermore, Table 5 details the number of references per reference category. Our reference category of interest is "scientific references", i.e., standard-relevant publications. However, scientific references constitute only a tiny proportion of the references in the standards. Only 78 or 4.2 % of all references in the standards are scientific publications. In relative terms, ISO standards reference more scientific publications than IEC standards (4.5 % vs. 3.8 %). Instead, normative references are predominant. 1571 or 85.4 % of all references

[5] Here, we refer to the IPC classes of patents filed by the leading 50 current assignees.

[6] The remaining non-patent citations, which were not available in the WoS, included reports, books, standards, etc.

Table 2
Publications by research institution.

General hydrogen research				Hydrogen safety research			
Rank	Institution	Records, (%)	Country	Rank	Institution	Records, (%)	Country
1	Chinese Academy of Sciences	8097 (5.1)	China	1	U.S. Department of Energy	1344 (4.2)	USA
2	U.S. Department of Energy	4949 (3.1)	USA	2	Chinese Academy of Sciences	1130 (3.5)	China
3	Centre National de la Recherche Scientifique (CNRS)	4535 (2.9)	France	3	Russian Academy of Sciences	901 (2.8)	Russia
4	University of California System	3051 (1.9)	USA	4	Centre National de la Recherche Scientifique (CNRS)	880 (2.7)	France
5	Russian Academy of Sciences	2462 (1.6)	Russia	5	University of California System	763 (2.4)	USA
6	Helmholtz Association	2301 (1.5)	Germany	6	Helmholtz Association	738 (2.3)	Germany
7	University of Chinese Academy of Sciences	2122 (1.3)	China	7	Indian Institute of Technology System	503 (1.6)	India
8	Indian Institute of Technology System	1949 (1.2)	India	8	Max Planck Society	447 (1.4)	Germany
9	Max Planck Society	1811 (1.1)	Germany	9	Tsinghua University	383 (1.2)	China
10	Zhejiang University	1710 (1.1)	China	10	Kyushu University	340 (1.1)	Japan
11	Consejo Superior de Investigaciones Científicas	1573 (1.0)	Spain	11	Université Paris Saclay	329 (1.0)	France
12	Consiglio Nazionale delle Ricerche	1495 (0.9)	Italy	12	Karlsruher Institut für Technologie	328 (1.0)	Germany
13	Council of Scientific and Industrial Research	1474 (0.9)	India	13	Sandia National Laboratory	327 (1.0)	USA
14	CNRS Institute of Chemistry	1407 (0.9)	France	14	University of Tokyo	323 (1.0)	Japan
15	Tsinghua University	1352 (0.9)	China	15	Xi An Jiaotong University	321 (1.0)	China
16	University of Science Technology of China	1294 (0.8)	China	16	University of California Berkeley	314 (1.0)	USA
17	National Institute of Advanced Industrial Science and Technology	1292 (0.8)	Japan	17	University of Science Technology of China	296 (0.9)	China
18	Tohoku University	1162 (0.7)	Japan	18	Tohoku University	294 (0.9)	Japan
19	Harbin Institute of Technology	1151 (0.7)	China	19	Consejo Superior de Investigaciones Científicas	279 (0.9)	Spain
20	Tianjin University	1147 (0.7)	China	20	University of Science Technology Beijing	274 (0.9)	China
	Total	158409			Total	32189	

Table 3
Publications by research area.

General hydrogen research			Hydrogen safety research		
Rank	Research area	Records, (%)	Rank	Research area	Records, (%)
1	Chemistry	85071 (53.7)	1	Energy fuels	10577 (32.9)
2	Energy fuels	37020 (23.4)	2	Chemistry	10283 (31.9)
3	Materials science	35861 (22.6)	3	Engineering	9878 (30.7)
4	Engineering	27019 (17.1)	4	Materials science	6930 (21.5)
5	Electrochemistry	25468 (16.1)	5	Electrochemistry	4781 (14.9)
6	Physics	22910 (14.5)	6	Physics	4359 (13.5)
7	Science technology, other	19286 (12.2)	7	Thermodynamics	3772 (11.7)
8	Biochemistry/ molecular biology	8201 (5.2)	8	Metallurgy/ metallurgical engineering	3188 (9.9)
9	Environmental sciences/ecology	7544 (4.8)	9	Science technology, other	2240 (7.0)
10	Metallurgy/ metallurgical engineering	6015 (3.8)	10	Nuclear science technology	2177 (6.8)
11	Biotechnology/ applied microbiology	5318 (3.4)	11	Environmental sciences/ecology	1400 (4.3)
12	Thermodynamics	3945 (2.5)	12	Mechanics	1029 (3.2)
13	Polymer science	3688 (2.3)	13	Astronomy/ astrophysics	983 (3.1)
14	Nuclear science technology	2780 (1.8)	14	Optics	662 (2.1)
15	Biophysics	2678 (1.7)	15	Instrumentation	560 (1.7)
	Total	158409		Total	32189

are cross-references to other standards (83.9 % for ISO, 87.8 % for IEC). Finally, other references, such as regulations, directives, or guidelines, constitute the third category. 191 or 10.4 % of the references are categorized as "other references" (11.6 % for ISO, 8.4 % for IEC).

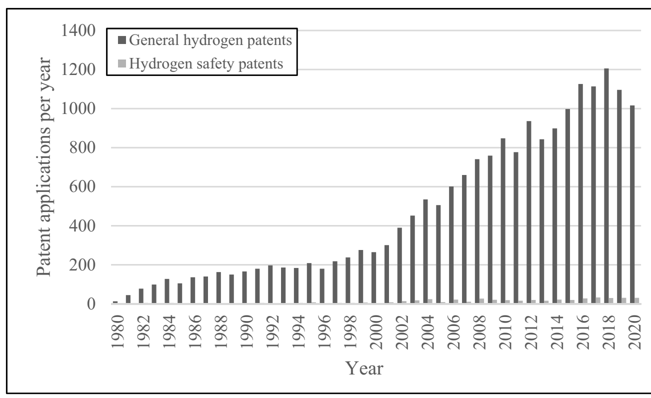

Fig. 3. Evolution of general hydrogen and hydrogen safety patent applications.

Overall, standard-relevant publications are concentrated in a small number of standards. Only six ISO and eight IEC standards cite scientific publications. However, we observe a growing trend. 63 out of 78 scientific references are found in standards published since 2017. To obtain further patterns in the standard-relevant publications, we analyzed 27 out of the 78 publications available in the WoS. Table 7 ranks the most frequently cited institutions and their home countries. North American and European institutions dominate this ranking, with the *University of South Carolina System* topping the list. Thus, the home countries of the institutions (Table 7) mirror those of the publications analyzed above (Table 1).

Furthermore, technical research areas predominate in both publications (Table 3) and standard-relevant publications (Table 6). However, the institutions identified in the list of publications (Table 2) and cited publications (Table 7) differ. This reveals that the most productive institutions, in general, and in hydrogen safety research, do not produce standard-relevant publications.

Table 8 breaks down 'other references' in hydrogen standards, including regulations, directives, and codes. Both are of great importance to hydrogen safety and can be conducive to innovation (Blind

Table 4
Patent applications by current assignee.

General hydrogen patents				Hydrogen safety patents			
Rank	Current assignee	Patents	Country	Rank	Current assignee	Patents	Country
1	Nissan Motor Co. Ltd.	1105	Japan	1	Commissariat à l'Energie Atomique SA	24	France
2	Toyota Motor Co.	820	Japan	2	Panasonic Co.	20	Japan
3	Honda Motor Co. Ltd.	687	Japan	3	AUDI AG	17	Germany
4	Panasonic Co.	605	Japan	4	Toyota Motor Co.	12	Japan
5	Commissariat à l'Energie Atomique SA	323	France	5	Illinois Tool Works Inc.	11	USA
6	Panasonic IP Management Co. Ltd	297	Japan	6	Nissan Motor Co. Ltd.	10	Japan
7	Samsung SDI Co. Ltd.	280	South Korea	7	Siemens AG	10	Germany
8	Panasonic IP Management	236	Japan	8	Arkema Inc.	9	France
9	Intelligent Energy Ltd.	232	UK	9	LG Fuel Cell Systems Inc.	9	South Korea
10	AUDI AG	214	Germany	10	Forschungszentrum Jülich GmbH	7	Germany
11	Siemens AG	202	Germany	11	Solvay S.A.	7	Germany
12	FuelCell Energy Inc.	193	USA	12	UTC Fuel Cells LLC	7	USA
13	Morimura SOFC Technology Co.	189	Japan	13	Airbus Operations GmbH	6	Germany
14	LG Chem Ltd.	173	South Korea	14	BlackBerry Ltd.	6	Canada
15	Forschungszentrum Jülich GmbH	172	Germany	15	Hexis AG	6	Switzerland
	Total	8936			Total	342	

Table 5
Standard references by ISO and IEC.

Standardization organization	ISO	IEC	Total
Number of standards	50	25	75
Average references per standard	23	28	25
Total references	1137	703	1840
Normative references (Share of total references)	954 (83.9 %)	617 (87.8 %)	1571 (85.4 %)
ISO/IEC standards (Share of normative references)	733 (76.8 %)	553 (89.6 %)	1286 (81.9 %)
Scientific references (Share of total references)	51 (4.5 %)	27 (3.8 %)	78 (4.2 %)
Other references (Share of total references)	132 (11.6 %)	59 (8.4 %)	191 (10.4 %)

Table 6
Standard-relevant publications – research areas.

Rank	Research area	Times referenced	Share of 27 references (in %)
1	Chemistry	18	66.7
2	Electrochemistry	16	59.3
3	Energy fuels	12	44.4
4	Materials science	8	29.6
5	Physics	3	11.1
6	Engineering	2	7.4
7	Instrumentation	2	7.4
8	Astronomy/astrophysics	1	3.7
9	Biochemistry/molecular biology	1	3.7
10	Business/economics	1	3.7
11	Computer science	1	3.7
12	Education/educational research	1	3.7
13	Spectroscopy	1	3.7
14	Thermodynamics	1	3.7

et al., 2017).

5. Discussion

Our findings provide essential insights into the knowledge flows within the hydrogen TIS (Markard, 2020). Before assessing the current phase of the hydrogen TIS life cycle, we discuss the interplay between publications, patents, and standards, which we used as proxies.

Table 7
Standard-relevant publications – institutions.

Rank	Institution	Times referenced	Share of 27 WoS references (in %)	Country
1	University of South Carolina System	6	22.2	USA
2	Laboratory of the Government Chemist	3	11.1	UK
3	National Research Council Canada	3	11.1	Canada
4	Ulster University	3	11.1	USA
5	University of Connecticut	3	11.1	USA
6	Ballard Power Systems Inc.	3	11.1	Canada
7	Helmholtz Association	2	7.4	Germany
8	Brown University	1	3.7	USA
9	Commissariat à l'Énergie Atomique	1	3.7	France
10	Chinese Academy of Sciences	1	3.7	China
11	Dalian Institute of Chemical Physics	1	3.7	China
12	Durham University	1	3.7	USA
13	Fachhochschule Niederrhein	1	3.7	Germany
14	German Aerospace Centre DLR	1	3.7	Germany
15	Headwaters Nanokinetix Inc.	1	3.7	USA

Table 8
Distribution of other references.

Other references	ISO	IEC	Total
Guides/guidance/guidelines/vocabularies	61	33	94
Regulations	12	0	12
Directives	13	0	13
Codes	5	5	10
Recommendations	12	3	15
Test protocols/procedures (not guidance)	2	7	9
Graphical symbols/diagrams/tables	0	6	6
Reports	5	2	7
Other documents	22	1	23

5.1. The interplay between publications and patents

Hydrogen publications, patents, and standards generally show a weak interplay. Our analysis revealed that knowledge and technology transfer from publications to patents is low (Callaert et al., 2006). Blind et al. (2018) found that the transfer intensifies with an increasing number of researchers active in patenting as they enhance knowledge and technology transfer from publications to patents. Researchers are more likely to cite their publications in the relevant field when patenting (Blind et al., 2022a, 2022b; Blind et al., 2018; Buggenhagen and Blind, 2022). However, researchers face constraints on time to engage in activities beyond publishing. For instance, they also have different preferences for either publishing or patenting (Blind et al., 2022a, 2022b; Blind et al., 2018).

The dominating industry-owned patents have a weaker link to scientific publications (Blind et al., 2018; Callaert et al., 2006). Moreover, studies on other technology fields, too, find these industry-owned patents weakly based on scientific publications (Blind et al., 2018; Callaert et al., 2006). As a result, an apparent discrepancy between scientific publications, primarily driven by academic researchers, and commercially oriented patents, driven by industry, is responsible for the low number of non-patent citations. Industry-owned patents are the primary type of patent applications worldwide. Thus, few academic researchers are currently involved in hydrogen patenting, i.e., the commercialization of scientific evidence revealed in publications is limited. The low "science intensity" is further amplified by the different institutions involved in publishing and patenting. There is hardly any coincidence between the most influential research institutions and patent assignees. However, there are also exceptions regarding the interplay between publications and patents. For instance, in 5G technologies, which are much more commercialized than hydrogen technologies, patent assignees and highest-publishing institutions broadly correspond (Buggenhagen and Blind, 2022). In that case, scientific publications, patents, and standards are closely linked.

Taking a step back, the interplay between the three knowledge and technology transfer channels indicates new technologies' maturity. Hullmann and Meyer (2003) confirm that patenting lags behind basic research in emerging technologies due to the time required to transpose the latest scientific knowledge from publications into patents. Dedehayir and Mäkinen (2011) describe this time lag as the technological industry clockspeed, i.e., "the time between successively higher levels of performance in the industry's product technology evolution". Sick et al. (2018) further specify these higher performance levels in technology development by referring to scientific publications as the first "stage" of the R&D profile in a technology life cycle, followed by patents as applied research (see also Watts and Porter, 1997) or as input for technology adoption-relevant policies (Collantes and Sperling, 2008). The technological industry clockspeed is determined by the length of the time lag between consecutive performance levels. In our data, we observe that the patterns of general hydrogen patent applications lag behind those of general hydrogen publications by 23–25 years in absolute terms (Fig. 4), i.e., the peak in patent applications in 2018 corresponds to the number of publications between 1995 and 1997. Therefore, the industry clockspeed of hydrogen technologies is slow, indicating that the hydrogen TIS life cycle is still in its emerging phase (cf. Dedehayir and Mäkinen, 2011; Sick et al., 2018). This does not imply that hydrogen technologies per se are not mature. As such, hydrogen technologies have already been safely used in the chemical and petrochemical industries for decades (Ball and Wietschel, 2009; Singh et al., 2015). Furthermore, technological advances have been reached along the hydrogen value chain, such as more effective hydrogen storage (Ball and Wietschel, 2009). However, the greater hydrogen innovation system, including its commercialization and market development, is still in its infancy. The development of hydrogen technologies is not yet commercially viable with respect to economies of scale (Al-Amin and Doberstein, 2019) and had not received enough policy support before numerous countries have adopted hydrogen strategies since 2020 (Albrecht et al., 2020; IEA, 2022). Furthermore, they face competition from other technologies, e.g., battery technologies in mobility.

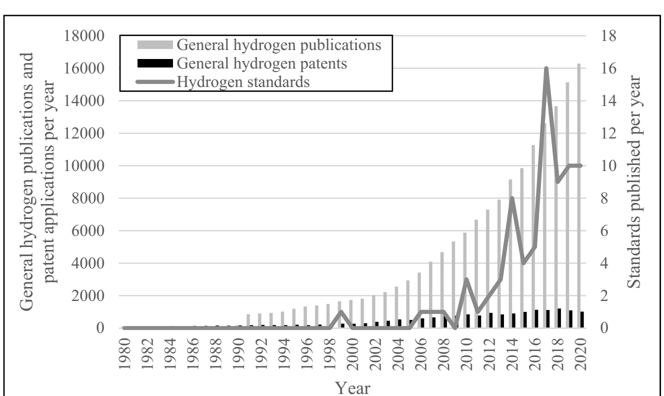

Fig. 4. Evolution of general hydrogen publications, patents, and standards compared.

Therefore, contrary to more commercialized technologies like batteries (Sick et al., 2018), hydrogen technologies have been more science-oriented (publications) than application-oriented (patents and standards). The gap between publications and patents highlights that applied research, including the transfer from basic to applied research, must be intensified for hydrogen technologies to close this gap and advance in the TIS life cycle. Here, a stronger alignment of the channels would amplify the maturity of the TIS (cf. Buggenhagen and Blind, 2022; Hullmann and Meyer, 2003; Sick et al., 2018).

Noting a discrepancy between the amount of hydrogen research (publications) and patenting, especially in hydrogen safety, we investigated the link between publications and patents in more depth. The analysis of NPL in hydrogen safety patents showed that only 47 or 14 % of patent documents contained NPL, respectively, while 22 records were available in the WoS. This indicates a low science intensity of hydrogen patents. Despite the low number of non-patent citations, the analysis of NPL validates the findings of our bibliometric publication analysis (Section 4.1). The ranking of countries in publications cited as NPL (Table A.2) partly corresponds to hydrogen safety publications (Table 1). As a specific result, those countries conduct hydrogen safety research relevant to hydrogen safety patents. However, China, one of the leading countries in hydrogen research, does not contribute to any publications relevant to hydrogen safety patents filed at the EPO. Generally speaking, Chinese firms have barely filed any hydrogen safety patents at the EPO. Instead, they primarily file their patents at the *China Patent & Trademark Office* (CPTO). There, Chinese NPL publications are more frequently cited. According to the IPlytics database (IPlytics, 2021), 50092 general hydrogen and 5702 hydrogen safety patents were filed at the CPTO between 1980 and 2020. This reveals that domestic patenting activities are much higher than the international level for three reasons: 1.) Patenting in China is strongly driven by financial incentives for patent assignees (Böing, 2020); 2.) The Chinese hydrogen market is more attractive to Chinese patent assignees, thus driving domestic patenting (Archibugi, 1992); 3.) The benchmark for granting patent applications at the CPTO is lower, thus giving rise to a high number of lower-quality patents (Böing, 2020).

Data from other patent offices show similar patterns. For example, high patenting activities are observable in Japan (62223 general patents and 3108 safety patents), the USA (21256 general patents and 807 safety patents), and South Korea (12150 general patents and 631 safety patents). The higher numbers of patent applications outside the EPO show that companies have filed more patents in their domestic markets or countries with more developed national hydrogen markets. Companies tend to file patents in markets that are already important or in markets that are likely to become important (Archibugi, 1992). As of 2021, 90 % of the world's fuel cell vehicles in stock are located in Japan, the USA, South Korea, and China, where the hydrogen markets are relatively developed (Plötz, 2022). As a result, against this background, hydrogen patenting at the EPO lags behind these four countries (see Table A.3,

Appendix A).

5.2. The interplay between publications and standards

In this study, we analyzed standard-relevant publications in international hydrogen standards to investigate the interplay between hydrogen publications and standards (see Blind and Fenton, 2022). In general, most internationally harmonized hydrogen standards have been published recently. Since 2017, 46 out of 75 ISO and IEC hydrogen standards have been published (Fig. 4). Only 14 of those standards cite scientific publications. Similar to the NPL, researchers are the driving force for standard-relevant publications. Empirical evidence of standard-relevant publications by Blind and Fenton (2022) confirms that the researchers' involvement in standardization creates a "science push of knowledge utilization." Researchers may be involved in standardization as members of TCs or as experts. However, they also face a trade-off between their engagement in publishing and standardization (Blind and Gauch, 2009; Blind et al., 2018). Blind et al. (2018) show that researchers have different preferences for publishing, patenting, and standardization. The authors distinguish between the 'gold' (financial reward), the 'ribbon' (reputation), and the 'puzzle' (intrinsic satisfaction) (Blind et al., 2022a, 2022b; Blind et al., 2018) to classify researchers' preferences. Accordingly, researchers' motives to publish and patent are driven by the impact on their reputation ('ribbon') and the pursuit of financial objectives ('gold'). Publications allow researchers to increase their reputation and influence in the scientific community. Thus, researchers are incentivized to publish in order to get recognition in their research communities.

In contrast, participation in standardization is primarily intrinsically driven ('puzzle')and barely associated with financial or reputational benefits, thus being least attractive to researchers in the triad (Blind et al., 2018). However, standardization and standards are important along the whole R&D process with increasing demand as technology progresses (Blind and Gauch, 2009). Aligning or more strongly translating publications into patents and standards is necessary throughout the entire innovation process to support progress from basic research via applied research toward market diffusion (Blind and Gauch, 2009). Although a strong interplay between publications, patents, and standards is critical to the innovation process, the knowledge and technology transfer from scientific publications to standards is limited across all types and areas of standards. Blind and Fenton (2022) show that ISO standards generally have few scientific references or standard-relevant publications. This is in line with hydrogen standards having only very few standard-relevant publications (see Table 5).

Therefore, Blind and Fenton (2022) suggest that participants in standardization cite scientific publications explicitly rather than using them mainly implicitly as input. Readjusting incentives could encourage more active involvement of researchers in the standardization process (see Blind et al., 2018): For instance, if researchers' contributions to standards development are more strongly acknowledged, this could lead to a more significant reputational effect ('ribbon') beyond intrinsic motivation ('puzzle'). Being more actively involved and acknowledged as contributing to standards could increase the researchers' visibility and, thus, their credibility as experts in their scientific communities. Regardless of the extent of knowledge and technology transfer in standards, basic research generally precedes applied research, i.e., patents and standards, by some time (Blind and Fenton, 2022) depending on the technological industry clockspeed (Dedehayir and Mäkinen, 2011; Sick et al., 2018). Therefore, more recently published ISO and IEC hydrogen standards cited scientific publications more frequently in our dataset (see Section 4.3).

If standardization succeeded in overcoming the various barriers to scientists (Blind et al., 2018), the interplay between publications and standards could be enhanced, thus contributing to intensified knowledge and technology transfer, which may eventually trickle down to market diffusion (Blind and Gauch, 2009).

5.3. Analyzing the global hydrogen TIS

We investigated publications, patents, and standards to explore the global hydrogen TIS and its life cycle phases (Markard, 2020). To determine the maturity of the hydrogen TIS, we first define the distinct characteristics of the formative and growth phases. Since hydrogen technologies are novel in terms of commercialization and market size, we do not consider the characteristics of the maturity and growth phase. According to Markard et al. (2020), four levels of analysis determine the TIS life cycle phase. Among others, these include the size and actor base, and institutional structure.

In the formative phase, the size and actor base are small, and there is little growth. Furthermore, the market is hardly dynamic, with only a few market entries and exits (Bergek et al., 2008; Markard, 2020). In contrast, in the growth phase, an increasing number of actors enters and causes a higher level of competition, including a struggle over standards and higher sales (Bergek et al., 2008; Markard, 2020). We apply these size and actor base characteristics in the formative and growth phase to our publication and patent analysis to classify them according to Markard's (2020) TIS life cycle.

The exponentially rising number of publications, primarily in general hydrogen research (Fig. 2), shows rapid growth. Hydrogen is attracting more and more research institutions and researchers covering various aspects of the hydrogen value chain. Therefore, if the size and the actor base of the hydrogen TIS are judged by publications alone, the hydrogen TIS exhibits elements of the growth phase.

In contrast, recent growth in hydrogen patent applications points to less pronounced growth in size and actor base. Instead, we observe a stagnating trend rather than sustained growth in the TIS; particularly, patenting in hydrogen safety is very low. As a result, potential assignees might have been hesitant to enter the hydrogen market and, thus, invested only limited R&D funds or filed a few patents (see Bakker, 2010a,b). On the other hand, the stagnating trend in patenting could be a sign of saturation and, thus, less pronounced growth (Ernst, 1997). However, our data does not capture the latest developments in the political hydrogen landscape. Since 2020, 22 countries have published national hydrogen strategies to promote their hydrogen economies (Albrecht et al., 2020; IEA, 2022). An additional 20 countries have announced to develop a hydrogen strategy (IEA, 2022). Therefore, this change in the framework conditions is likely to support more innovation in the form of hydrogen patenting in the future. Although the patterns of hydrogen patenting and, in particular, safety patenting exhibit characteristics of the formative phase (Markard, 2020) of the hydrogen TIS, the hydrogen strategies are likely to incentivize industries to commercialize hydrogen technologies and lead to a growing TIS.

To classify hydrogen standards, we first describe the characteristics of the dimension "institutional structure & networks" in the formative and growth phase. In the formative phase, there is a low degree of structuration, poorly established value chains, and loose networks (Markard, 2020). In the growth phase, structuration increases, the market grows, and institutions specifically dealing with the technology emerge (Markard, 2020). Using standards as an indicator of the institutional structure of the hydrogen TIS, the increased standards development is a sign of formalization and structuration. The guiding function of standards helps actors coordinate their actions (Abbott and Snidal, 2001). Especially since recently, ISO and IEC have been working intensively on hydrogen standardization. Although the (international) hydrogen market has not yet taken shape, standards are vital to its ramp-up. They increase the safety of hydrogen applications and thus facilitate their market entry (Ambrose et al., 2017; Dincer and Acar, 2017). Even if not all conditions for the TIS in the growth phase are fulfilled, the increasing structuration of the hydrogen TIS by standards proves that hydrogen standards have growth phase characteristics. The evidence of Blind et al. (2021) proves that international standards have a growth-enhancing effect. Therefore, the development of the hydrogen TIS and the hydrogen market ramp-up necessitate this crucial driver for improved safety and economic growth. Again, the change in the framework conditions, such as the hydrogen strategies, or standardization roadmaps (NOW GmbH, 2019), is likely to support hydrogen standardization in the future and generate more knowledge flows to the benefit of the overall hydrogen TIS. The analyses and discussion have shown that patenting and, to some extent, standardization is lagging behind publications. This tremendous time lag described as the technological industry clockspeed highlights the need for continued technology development in the hydrogen TIS, also with respect to hydrogen safety. In this respect, the interplay between hydrogen publications, patents, and standards (Blind and Fenton, 2022; Blind et al., 2022a, 2022b; Blind et al., 2018) can contribute to an increased industry clockspeed that would favor the hydrogen TIS. An intensified interplay would allow the hydrogen TIS to form more quickly and become more mature, as evidence, e.g., from 5G technologies, shows (Buggenhagen and Blind, 2022; Hullmann and Meyer, 2003). All three channels could thus be aligned toward the hydrogen market ramp-up, and the hydrogen TIS could grow further. Furthermore, against the backdrop of competing TISs, e.g., fuel cell vehicles vs. electric vehicles, implementing more robust TIS structures is essential for introducing hydrogen technologies to the market. Therefore, reaching the successful hydrogen market ramp-up requires intensified knowledge and technology transfer that benefits the entire TIS, and, consequently, paves the way for a larger hydrogen market.

The third analytical dimension of a TIS refers to the performance and variation of the technology. Our bibliometric analysis does not address in detail this dimension but only gives a general overview of the patterns in research and technology development. However, research has extensively elaborated on the performance and maturity of hydrogen technologies. Among others, hydrogen storage and transportation technologies have to become more efficacious (Andrews and Shabani, 2014; Ball and Wietschel, 2009; Hassan et al., 2021), while the price of environmentally-friendly green hydrogen is not yet competitive. For instance, the production of green hydrogen is currently more expensive than grey and blue hydrogen and thus not economically viable for producers (Van Renssen, 2020).

Classifying the overall hydrogen TIS according to Markard's (2020) TIS life cycle phases shows mainly elements of hydrogen technologies in their formative phase. Although a growing trend toward more scientific research and a higher degree of structuration in the form of standards as R&D output can be observed, the hydrogen TIS mainly shows characteristics of a formative phase. Especially in terms of patents and other required criteria, the hydrogen TIS is not yet mature enough to be already in its growth phase. At this point, increasing the technological industry clockspeed would contribute to more TIS maturity. Although hydrogen research and efforts to standardize are increasing and facilitating the development of the TIS, further growth in commercially viable applications is necessary, especially in those measured by patents or larger market size. Eventually, the TIS will develop more quickly with a better alignment of the three knowledge and technology transfer channels.

6. Conclusion

In this research paper, we have explored the patterns in publications and patents related to hydrogen and hydrogen safety in particular, as well as to international hydrogen and fuel cell standards (*RQ1*). In addition, we have investigated the interplay between these three channels (*RQ2*) and approached them empirically against the backdrop of the life cycle of the hydrogen TIS (*RQ3*).

With our analysis of NPL in hydrogen safety-related patent documents, we have demonstrated that the transfer of knowledge and technology from publications to patents is not pronounced. Similarly, our analysis of ISO and IEC standards has shown that these refer only marginally, but in increasing numbers, to standard-relevant publications. The enhanced transfer of knowledge as the interplay between publications, patents, and standards will help facilitate the diffusion of hydrogen technologies. Furthermore, it will enable the development of safer and more advanced hydrogen technologies and their market introduction.

The hydrogen TIS is currently in its formative phase while already showing elements of the growth phase. It requires an increased technological industry clockspeed, as well as additional rapid increases in sales, i.e., a hydrogen market, to grow further (Markard, 2020). There is an intensified knowledge and technology transfer from basic research to advanced technology development and market actors, as facilitated through publications, patents, and standards, hydrogen technology. However, hydrogen technologies have not yet reached their full technological and commercial readiness. For instance, the market introduction of hydrogen requires further improvements in technological performance, such as hydrogen storage and transportation (Andrews and Shabani, 2014; Ball and Wietschel, 2009; Hassan et al., 2021), policy support, and infrastructure development (Acar and Dincer, 2015; Karger and Bongartz, 2008; Kohler et al., 2010).

Our approach is not without limitations: We could not exclude all irrelevant records despite using adequate publication and patent data filters. Specifically for publication data, the WoS analysis tool counts each country, institution, and research area involved in the article as one unit. Therefore, the influence of some of these parameters might be overrepresented by our data. Also, the number of records does not capture the quality and contribution of the records (Valenzuela et al., 2017). Additionally, our analysis uses patents as an indicator of innovation. However, not every innovation is patented (Arundel and Kabla, 1998). Alternatively, strategic motives may drive the decision to patent (Dziallas and Blind, 2019; Torrisi et al., 2016; Watts and Porter, 1997). In our analysis of hydrogen standards, we only considered international standards released by ISO and IEC for their better applicability to the international publication and patent analysis. However, hydrogen standards at regional and national levels also contribute to the formalization of the hydrogen innovation system. Lastly, this study cannot explain the entire hydrogen TIS but only some aspects of it. For instance, we have not analyzed the context structures of the TIS, such as comparable TISs in the clean energy sector like electric vehicles, to better understand the maturity of the hydrogen TIS.

Despite these limitations, the key takeaway from this study is that an intensified knowledge and technology transfer is essential to the increased maturity of the hydrogen TIS, thus paving the way for hydrogen technologies' market entry. Reducing the barriers to scientists to engage in applied hydrogen research could thus be a key enabler for an improved interplay between publications, patents, and standards to contribute to the hydrogen market ramp-up.

This study contributes to previous research at multiple levels: First, we contribute both empirically and conceptually to TIS and TIS life cycle research by using publications, patents, and standards as quantitative indicators. Second, we have investigated the three knowledge and technology channels and their interplay concerning hydrogen technology as a new application field. Third, our analysis identified further development requirements for the hydrogen TIS, including an increased technological industry clockspeed.

Future TIS research may use more extensively the three knowledge and technology transfer channels for the analysis of TISs and their maturity. At the same time, quantitative TIS analyses should be more aligned with qualitative analyses of key factors affecting TIS development. Furthermore, the perspective of market development and technology diffusion in a TIS can be investigated more extensively (Blind and Jungmittag, 2007; Grossman and Helpman, 1991; Rogers, 1983). Finally, analyses of comparable TISs are necessary for future research to better understand the context structures of the hydrogen TIS.

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CRediT authorship contribution statement

Parsa Asna Ashari: Conceptualization, Methodology, Formal analysis, Writing, Supervision. **Knut Blind**: Conceptualization, Methodology, Writing. **Claudia Koch**: Conceptualization, Methodology, Writing.

Declaration of competing interest

None.

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.

Data availability

Data will be made available on request.

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Appendix A. WoS analysis of NPL in hydrogen safety patents

Table A.1
WoS analysis of NPL – research areas.

Rank	Research areas	Records, (share in %)
1	Energy fuels	10 (45.5)
2	Electrochemistry	9 (40.9)
3	Materials science	8 (36.4)
4	Chemistry	6 (27.3)
5	Engineering	5 (22.7)
6	Optics	2 (9.1)
7	Instruments/instrumentation	1 (4.5)
8	Mathematics	1 (4.5)
9	Mechanics	1 (4.5)
10	Microbiology	1 (4.5)
11	Nuclear science technology	1 (4.5)
12	Polymer science	1 (4.5)
	Total	22 (100)

Table A.2
WoS analysis of NPL – countries.

Rank	Country	Records, (share in %)
1	USA	7 (31.8)
2	Japan	6 (27.3)
3	Germany	3 (13.6)
4	England	2 (9.1)
5	Austria	1 (4.5)
6	Canada	1 (4.5)
7	France	1 (4.5)
8	Netherlands	1 (4.5)
9	South Korea	1 (4.5)
10	Turkey	1 (4.5)
	Total	22(100)

Table A.3
Global hydrogen patenting – highest assigning countries globally, 1980–2020, Espacenet (2021).

Rank	Country	Records
1	Japan	42212
2	USA	41109
3	South Korea	24582
4	Germany	17313
5	China	8789
6	France	6273
7	UK	4135
8	Canada	4108
9	Taiwan	3367
10	Netherlands	1717
11	Russia	1604
12	Switzerland	1571

(*continued on next page*)

Table A.3 (*continued*)

Rank	Country	Records
13	Italy	1369
14	Denmark	974
15	Soviet Union	847
16	Sweden	680
17	Belgium	605
18	Spain	582
19	Australia	544
20	Austria	519
	Total	170039

References

Abbas, A., Zhang, L., Khan, S.U., 2014. A literature review on the state-of-the-art in patent analysis. World Patent Inf. 37, 3–13. https://doi.org/10.1016/j.wpi.2013.12.006.

Abbott, K.W., Snidal, D., 2001. International 'standards' and international governance. J. Eur. Publ. Policy 8 (3), 345–370. https://doi.org/10.1080/13501760110056013.

Abdel-Wahab, M., Ali, D., 2013. A conceptual framework for the evaluation of fuel-cell energy systems in the UK built environment. Int. J. Green Energy 10 (2), 137–150. https://doi.org/10.1080/15435075.2011.642089.

Acar, C., Dincer, I., 2015. Impact assessment and efficiency evaluation of hydrogen production methods. Int. J. Energy Res. 39 (13), 1757–1768. https://doi.org/10.1002/er.3302.

Al-Amin, A.Q., Doberstein, B., 2019. Introduction of hydrogen fuel cell vehicles: prospects and challenges for Malaysia's transition to a low-carbon economy. Environ. Sci. Pollut. Res. 26 (30), 31062–31076. https://doi.org/10.1007/s11356-019-06128-4.

Albrecht, U., Bünger, U., Michalski, J., Raksha, T., Wurster, R., Zerhusen, J., 2020. International Hydrogen Strategies. A study commissioned by and in cooperation with the World Energy Council Germany. Retrieved from. https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf.

Ambrose, A.F., Al-Amin, A.Q., Rasiah, R., Saidur, R., Amin, N., 2017. Prospects for introducing hydrogen fuel cell vehicles in Malaysia. Int. J. Hydrog. Energy 42 (14), 9125–9134. https://doi.org/10.1016/j.ijhydene.2016.05.122.

Andrews, J., Shabani, B., 2014. The role of hydrogen in a global sustainable energy strategy. Wiley Interdiscip. Rev. Energy Environ. 3 (5), 474–489. https://doi.org/10.1002/wene.103.

Andwari, A.M., Pesiridis, A., Rajoo, S., Martinez-Botas, R., Esfahanian, V., 2017. A review of battery electric vehicle technology and readiness levels. Renew. Sustain. Energy Rev. 78, 414–430. https://doi.org/10.1016/j.rser.2017.03.138.

Aprea, J.L., 2008. New standard on safety for hydrogen systems in Spanish keys for understanding and use. Int. J. Hydrog. Energy 33 (13), 3526–3530. https://doi.org/10.1016/j.ijhydene.2008.02.066.

Aprea, J.L., 2014. Quality specification and safety in hydrogen production, commercialization and utilization. Int. J. Hydrog. Energy 39 (16), 8604–8608. https://doi.org/10.1016/j.ijhydene.2014.01.005.

Archibugi, D., 1992. Patenting as an indicator of technological innovation: a review. Sci. Public Policy 19 (6). https://doi.org/10.1093/spp/19.6.357.

Arundel, A., Kabla, I., 1998. What percentage of innovations are patented? Empirical estimates for European firms. Res. Policy 27 (2), 127–141. https://doi.org/10.1016/s0048-7333(98)00033-x.

Bakker, S., 2010a. The car industry and the blow-out of the hydrogen hype. Energy Policy 38 (11), 6540–6544. https://doi.org/10.1016/j.enpol.2010.07.019.

Bakker, S., 2010b. Hydrogen patent portfolios in the automotive industry - the search for promising storage methods. Int. J. Hydrog. Energy 35 (13), 6784–6793. https://doi.org/10.1016/j.ijhydene.2010.04.002.

Ball, M., Wietschel, M., 2009. The future of hydrogen – opportunities and challenges. Int. J. Hydrog. Energy 34 (2), 615–627. https://doi.org/10.1016/j.ijhydene.2008.11.014.

Behling, N., 2013. Current global fuel cell R&D and future research needs. ECS Trans. 51 (1), 3–26. https://doi.org/10.1149/05101.0003ecst.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Res. Policy 37 (3), 407–429. https://doi.org/10.1016/j.respol.2007.12.003.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Trans. 16, 51–64. https://doi.org/10.1016/j.eist.2015.07.003.

Besley, J.C., Baxter-Clemmons, S., 2010. Analysis of South Carolina hydrogen and fuel cell workers views and opinion leadership behavior: a waiting opportunity? Int. J. Hydrog. Energy 35 (16), 8407–8416. https://doi.org/10.1016/j.ijhydene.2010.06.002.

Blanco, H., Nijs, W., Ruf, J., Faaij, A., 2018. Potential for hydrogen and power-to-liquid in a low-carbon EU energy system using cost optimization. Appl. Energy 232, 617–639. https://doi.org/10.1016/j.apenergy.2018.09.216.

Blind, K., 2004. The Economics of Standards - Theory, Evidence, Policy. Edward Elgar, Cheltenham, Northampton.

Blind, K., Fenton, A., 2022. Standard-relevant publications: evidence, processes and influencing factors. Scientometrics. https://doi.org/10.1007/s11192-021-04210-8.

Blind, K., Gauch, S., 2009. Research and standardisation in nanotechnology: evidence from Germany. J. Technol. Transfer. 34 (3), 320–342. https://doi.org/10.1007/s10961-008-9089-8.

Blind, K., Jungmittag, A., 2007. The impact of patents and standards on macroeconomic growth: a panel approach covering four countries and 12 sectors. J. Prod. Anal. 29 (1), 51–60. https://doi.org/10.1007/s11123-007-0060-8.

Blind, K., Petersen, S., Riillo, C., 2017. The impact of standards and regulation on innovation in uncertain markets. Res. Policy 46 (1), 249–264. https://doi.org/10.1016/j.respol.2016.11.003.

Blind, K., Pohlisch, J., Zi, A., 2018. Publishing, patenting, and standardization: motives and barriers of scientists. Res. Policy 47 (7), 1185–1197. https://doi.org/10.1016/j.respol.2018.03.011.

Blind, K., Ramel, F., Rochell, C., 2021. The influence of standards and patents on long-term economic growth. J. Technol. Transf. https://doi.org/10.1007/s10961-021-09864-3.

Blind, K., Filipović, E., Lazina, L.K., 2022a. Motives to publish, to patent and to standardize: an explorative study based on individual engineers'assessments. Technol. Forecast. Soc. Chang. 175, 121420 https://doi.org/10.1016/j.techfore.2021.121420.

Blind, K., Krieger, B., Pellens, M., 2022b. The interplay between product innovation, publishing, patenting and developing standards. Res. Policy 51 (7), 104556. https://doi.org/10.1016/j.respol.2022.104556.

Bockris, J.O.M., 2013. The hydrogen economy: its history. Int. J. Hydrog. Energy 38 (6), 2579–2588. https://doi.org/10.1016/j.ijhydene.2012.12.026.

Bockris, J.O.M., Appleby, A., 1972. The hydrogen economy-an ultimate economy. Environ. This Month 1 (1), 29–35.

Böing, P., 2020. Innovative China, R&D Subsidies, Patent Measures, and Productivity. ZEW-Kurzexpertise Nr. 20-15. Retrieved from. https://www.zew.de/publikationen/innovative-china.

Buggenhagen, M., Blind, K., 2022. Development of 5G – identifying organizations active in publishing, patenting, and standardization. Telecommun. Policy 46 (4), 102326. https://doi.org/10.1016/j.telpol.2022.102326.

Cairns, J., 2010. North American and international hydrogen/fuel cell standards. Int. J. Hydrog. Energy 35 (7), 2767–2771. https://doi.org/10.1016/j.ijhydene.2009.05.001.

Callaert, J., Van Looy, B., Verbeek, A., Debackere, K., Thijs, B., 2006. Traces of Prior Art: an analysis of non-patent references found in patent documents. Scientometrics 69 (1), 3–20. https://doi.org/10.1007/s11192-006-0135-8.

Chanchetti, L.F., Oviedo Diaz, S.M., Milanez, D.H., Leiva, D.R., de Faria, L.I.L., Ishikawa, T.T., 2016. Technological forecasting of hydrogen storage materials using patent indicators. Int. J. Hydrog. Energy 41 (41), 18301–18310. https://doi.org/10.1016/j.ijhydene.2016.08.137.

Chanchetti, L.F., Leiva, D.R., Lopes de Faria, L.I., Ishikawa, T.T., 2020. A scientometric review of research in hydrogen storage materials. Int. J. Hydrog. Energy 45 (8), 5356–5366. https://doi.org/10.1016/j.ijhydene.2019.06.093.

Chang, P.-L., Wu, C.-C., Leu, H.-J., 2010. Using patent analyses to monitor the technological trends in an emerging field of technology: a case of carbon nanotube field emission display. Scientometrics 82 (1), 5–19. https://doi.org/10.1007/s11192-009-0033-y.

Chen, Y.H., Chen, C.Y., Lee, S.C., 2011. Technology forecasting and patent strategy of hydrogen energy and fuel cell technologies. Int. J. Hydrog. Energy 36 (12), 6957–6969. https://doi.org/10.1016/j.ijhydene.2011.03.063.

Choi, H., Park, S., 2018. Network variations at the intersection of national capability orientation and technological path dependence – patent citation network analysis of the hydrogen energy and nano-tech sectors. Ind. Innov. 25 (8), 809–831. https://doi.org/10.1080/13662716.2017.1358605.

Chubin, D.E., Moitra, S.D., 1975. Content analysis of references: adjunct or alternative to citation counting? Soc. Stud. Sci. 5 (4), 423–441.

Collantes, G., Sperling, D., 2008. The origin of California's zero emission vehicle mandate. Transp. Res. A Policy Pract. 42 (10), 1302–1313. https://doi.org/10.1016/j.tra.2008.05.007.

Dedehayir, O., Mäkinen, S.J., 2011. Measuring industry clockspeed in the systemic industry context. Technovation 31 (12), 627–637. https://doi.org/10.1016/j.technovation.2011.07.008.

Dincer, I., Acar, C., 2017. Innovation in hydrogen production. Int. J. Hydrog. Energy 42 (22), 14843–14864. https://doi.org/10.1016/j.ijhydene.2017.04.107.

Dodds, P.E., Staffell, I., Hawkes, A.D., Li, F., Grünewald, P., McDowall, W., Ekins, P., 2015. Hydrogen and fuel cell technologies for heating: a review. Int. J. Hydrog. Energy 40 (5), 2065–2083. https://doi.org/10.1016/j.ijhydene.2014.11.059.
Dutta, S., 2014. A review on production, storage of hydrogen and its utilization as an energy resource. J. Ind. Eng. Chem. 20 (4), 1148–1156. https://doi.org/10.1016/j.jiec.2013.07.037.
Dziallas, M., Blind, K., 2019. Innovation indicators throughout the innovation process: an extensive literature analysis. Technovation 80–81, 3–29. https://doi.org/10.1016/j.technovation.2018.05.005.
Edwards, P.P., Kuznetsov, V.L., David, W.I.F., 2007. Hydrogen energy. Phil. Trans. R. Soc. A 365 (1853), 1043–1056. https://doi.org/10.1098/rsta.2006.1965.
Ernst, H., 1997. The use of patent data for technological forecasting: the diffusion of CNC-technology in the machine tool industry. Small Bus. Econ. 9 (4), 361–381. https://doi.org/10.1023/a:1007921808138.
Espacenet, 2021. Retrieved from. https://worldwide.espacenet.com/patent/search.
FCHEA, 2021. Hydrogen/Fuel Cell Codes & Standards. Retrieved from. http://www.fuelcellstandards.com/home.html.
Fowler, C.P., Orifici, A.C., Wang, C.H., 2016. A review of toroidal composite pressure vessel optimisation and damage tolerant design for high pressure gaseous fuel storage. Int. J. Hydrog. Energy 41 (47), 22067–22089. https://doi.org/10.1016/j.ijhydene.2016.10.039.
Garfield, E., Morton, V.M., Small, H., 1978. Citation data as science indicators. In: L.J., Elkana, Y., Merton, R.K., Thackray, A., Zuckerman, H. (Eds.), Toward a Metric of Science: The Advent of Science Indicators. John Wiley & Sons Press, New York.
Glänzel, W., Schoepflin, U., 1999. A bibliometric study of reference literature in the sciences and social sciences. Inf. Process. Manag. 35 (1), 31–44. https://doi.org/10.1016/S0306-4573(98)00028-4.
Glänzel, W., Schubert, A., Czerwon, H.J., 1999a. An item-by-item subject classification of papers published in multidisciplinary and general journals using reference analysis. Scientometrics 44 (3), 427–439. https://doi.org/10.1007/bf02458488.
Glänzel, W., Schubert, A., Schoepflin, U., Czerwon, H.J., 1999b. An item-by-item subject classification of papers published in journals covered by the SSCI database using reference analysis. Scientometrics 46 (3), 431–441. https://doi.org/10.1007/bf02459602.
Grossman, G., Helpman, E., 1991. Innovation and Growth in the Global Economy, Vol. 1. The MIT Press.
Hacking, N., Pearson, P., Eames, M., 2019. Mapping innovation and diffusion of hydrogen fuel cell technologies: evidence from the UK's hydrogen fuel cell technological innovation system, 1954–2012. Int. J. Hydrog. Energy 44 (57), 29805–29848. https://doi.org/10.1016/j.ijhydene.2019.09.137.
Hardman, S., Shiu, E., Steinberger-Wilckens, R., Turrentine, T., 2017. Barriers to the adoption of fuel cell vehicles: a qualitative investigation into early adopters attitudes. Transp. Res. Part A Policy Pract. 95, 166–182. https://doi.org/10.1016/j.tra.2016.11.012.
Hassan, I.A., Ramadan, H.S., Saleh, M.A., Hissel, D., 2021. Hydrogen storage technologies for stationary and mobile applications: review, analysis and perspectives. Renew. Sust. Energ. Rev. 149, 111311 https://doi.org/10.1016/j.rser.2021.111311.
He, M., Zhang, Y., Gong, L., Zhou, Y., Song, X., Zhu, W., Zhang, Z., 2019. Bibliometrical analysis of hydrogen storage. Int. J. Hydrog. Energy 44 (52), 28206–28226. https://doi.org/10.1016/j.ijhydene.2019.07.014.
Hou, W.R., Li, M., Niu, D.K., 2011. Counting citations in texts rather than reference lists to improve the accuracy of assessing scientific contribution: citation frequency of individual articles in other papers more fairly measures their scientific contribution than mere presence in reference lists. BioEssays 33 (10), 724–727. https://doi.org/10.1002/bies.201100067.
Hsu, C.-W., Chang, P.-L., Hsiung, C.-M., Lin, C.-Y., 2014. Commercial application scenario using patent analysis: fermentative hydrogen production from biomass. Int. J. Hydrog. Energy 39 (33), 19277–19284. https://doi.org/10.1016/j.ijhydene.2014.05.100.
Huang, M.-H., Yang, H.-W., Chen, D.-Z., 2015. Increasing science and technology linkage in fuel cells: a cross citation analysis of papers and patents. J. Informetrics 9 (2), 237–249. https://doi.org/10.1016/j.joi.2015.02.001.
Hullmann, A., Meyer, M., 2003. Publications and patents in nanotechnology. Scientometrics 58 (3), 507–527. https://doi.org/10.1023/b:scie.0000006877.45467.a7.
IEA, 2022. Global Hydrogen Review 2022. Retrieved from. https://www.iea.org/reports/global-hydrogen-review-2022.
IPlytics, 2021. Patents Search. Retrieved from. https://platform.iplytics.com/search.
ISO, 2021. ISO Online Browsing Platform. Retrieved from. https://www.iso.org/obp/ui#home.
Karger, C.R., Bongartz, R., 2008. External determinants for the adoption of stationary fuel cells - infrastructure and policy issues. Energy Policy 36 (2), 798–810. https://doi.org/10.1016/j.enpol.2007.10.024.
Keles, D., Wietschel, M., Most, D., Rentz, O., 2008. Market penetration of fuel cell vehicles – analysis based on agent behaviour. Int. J. Hydrog. Energy 33 (16), 4444–4455. https://doi.org/10.1016/j.ijhydene.2008.04.061.
Kikukawa, S., Mitsuhashi, H., Miyake, A., 2009. Risk assessment for liquid hydrogen fueling stations. Int. J. Hydrog. Energy 34 (2), 1135–1141. https://doi.org/10.1016/j.ijhydene.2008.10.093.
Ko, Y.-C., Zigan, K., Liu, Y.-L., 2021. Carbon capture and storage in South Africa: a technological innovation system with a political economy focus. Technol. Forecast. Soc. Chang. 166, 120633 https://doi.org/10.1016/j.techfore.2021.120633.
Kohler, J., Wietschel, M., Whitmarsh, L., Keles, D., Schade, W., 2010. Infrastructure investment for a transition to hydrogen automobiles. Technol. Forecast. Soc. Chang. 77 (8), 1237–1248. https://doi.org/10.1016/j.techfore.2010.03.010.
Konrad, K., Markard, J., Ruef, A., Truffer, B., 2012. Strategic responses to fuel cell hype and disappointment. Technol. Forecast. Soc. Chang. 79 (6), 1084–1098. https://doi.org/10.1016/j.techfore.2011.09.008.
Linke, G., 2009. A survey of gas infrastructure innovations. Oil Gas-Eur.Mag. 35 (3), 132–134. https://www.osti.gov/etdeweb/biblio/21246332.
Markard, J., 2020. The life cycle of technological innovation systems. Technol. Forecast. Soc. Chang. 153, 119407 https://doi.org/10.1016/j.techfore.2018.07.045.
Markard, J., Bento, N., Kittner, N., Nuñez-Jimenez, A., 2020. Destined for decline? Examining nuclear energy from a technological innovation systems perspective. Energy Res. Soc. Sci. 67, 101512 https://doi.org/10.1016/j.erss.2020.101512.
Markert, F., Nielsen, S., Paulsen, J., Andersen, V., 2007. Safety aspects of future infrastructure scenarios with hydrogen refuelling stations. Int. J. Hydrog. Energy 32 (13), 2227–2234. https://doi.org/10.1016/j.ijhydene.2007.04.011.
Mazloomi, K., Gomes, C., 2012. Hydrogen as an energy carrier: prospects and challenges. Renew. Sust. Energ. Rev. 16 (5), 3024–3033. https://doi.org/10.1016/j.rser.2012.02.028.
Najjar, Y.S.H., 2013. Hydrogen safety: the road toward green technology. Int. J. Hydrog. Energy 38 (25), 10716–10728. https://doi.org/10.1016/j.ijhydene.2013.05.126.
Narin, F., 1994. Patent bibliometrics. Scientometrics 30 (1), 147–155. https://doi.org/10.1007/bf02017219.
Norton, M., 2000. Introductory Concepts in Information Science. Information Today Inc.
NOW GmbH, 2019. Die Deutsche H_2-RCS-Roadmap 2025: RCS-Regulations, Codes & Standards, Regelwerke, Durchführungsbestimmungen & Normen im Bereich Wasserstoff (H_2). Retrieved from. https://www.now-gmbh.de/wp-content/uploads/2020/09/now_deutsche-h2-rcs-roadmap.pdf.
OECD, Eurostat, 2018. Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation. Retrieved from, 4th edition. https://www.oecd.org/science/oslo-manual-2018-9789264304604-en.htm.
Plötz, P., 2022. Hydrogen technology is unlikely to play a major role in sustainable road transport. Nat. Elect. 5 (1), 8–10. https://doi.org/10.1038/s41928-021-00706-6.
Rogers, E.M., 1983. Diffusion of Innovations, Third Edition. The Free Press: A Division of Macmillan Publishing Co., Inc., New York, pp. 8–10. https://doi.org/10.1038/s41928-021-00706-6.
Romejko, K., Nakano, M., 2017. Portfolio analysis of alternative fuel vehicles considering technological advancement, energy security and policy. J. Clean. Prod. 142, 39–49. https://doi.org/10.1016/j.jclepro.2016.09.029.
Sarkar, M.S.K., Al-Amin, A.Q., Filho, W.L., 2019. Revisiting the social cost of carbon after INDC implementation in Malaysia: 2050. Environ. Sci. Pollut. Res. 26 (6), 6000–6013. https://doi.org/10.1007/s11356-018-3947-1.
Schulte, I., 2004. Issues affecting the acceptance of hydrogen fuel. Int. J. Hydrog. Energy 29 (7), 677–685. https://doi.org/10.1016/j.ijhydene.2003.09.006.
Sick, N., Bröring, S., Figgemeier, E., 2018. Start-ups as technology life cycle indicator for the early stage of application: an analysis of the battery value chain. J. Clean. Prod. 201, 325–333. https://doi.org/10.1016/j.jclepro.2018.08.036.
Singh, S., Jain, S., Ps, V., Tiwari, A.K., Nouni, M.R., Pandey, J.K., Goel, S., 2015. Hydrogen: a sustainable fuel for future of the transport sector. Renew. Sust. Energ. Rev. 51, 623–633. https://doi.org/10.1016/j.rser.2015.06.040.
Sinigaglia, T., Freitag, T.E., Kreimeier, F., Martins, M.E.S., 2019. Use of patents as a tool to map the technological development involving the hydrogen economy. World Patent Inf. 56, 1–8. https://doi.org/10.1016/j.wpi.2018.09.002.
Suominen, A., 2014. Phases of growth in a green tech research network: a bibliometric evaluation of fuel cell technology from 1991 to 2010. Scientometrics 100 (1), 51–72. https://doi.org/10.1007/s11192-014-1285-8.
Suurs, R.A.A., Hekkert, M.P., Smits, R.E.H.M., 2009. Understanding the build-up of a technological innovation system around hydrogen and fuel cell technologies. Int. J. Hydrog. Energy 34 (24), 9639–9654. https://doi.org/10.1016/j.ijhydene.2009.09.092.
Torrisi, S., Gambardella, A., Giuri, P., Harhoff, D., Hoisl, K., Mariani, M., 2016. Used, blocking and sleeping patents: empirical evidence from a large-scale inventor survey. Res. Policy 45 (7), 1374–1385. https://doi.org/10.1016/j.respol.2016.03.021.
Tsay, M.-Y., 2008. A bibliometric analysis of hydrogen energy literature, 1965–2005. Scientometrics 75 (3), 421–438. https://doi.org/10.1007/s11192-007-1785-x.
Turinsky, P.J., Kothe, D.B., 2016. Modeling and simulation challenges pursued by the Consortium for Advanced Simulation of Light Water Reactors (CASL). J. Comput. Phys. 313, 367–376. https://doi.org/10.1016/j.jcp.2016.02.043.
Umweltbundesamt, 2020. Emissionsquellen. Retrieved from. https://www.umweltbundesamt.de/themen/klima-energie/treibhausgas-emissionen/emissionsquellen.
Valenzuela, L.M., Merigó, J.M., Johnston, W.J., Nicolas, C., Jaramillo, J.F., 2017. Thirty years of the Journal of Business & Industrial Marketing: a bibliometric analysis. J. Bus. Ind. Mark. 32 (1), 1–17. https://doi.org/10.1108/jbim-04-2016-0079.
van Oorschot, J.A.W.H., Hofman, E., Halman, J.I.M., 2018. A bibliometric review of the innovation adoption literature. Technol. Forecast. Soc. Chang. 134, 1–21. https://doi.org/10.1016/j.techfore.2018.04.032.
Van Renssen, S., 2020. The hydrogen solution? Nat. Clim. Chang. 10 (9), 799–801. https://doi.org/10.1038/s41558-020-0891-0.
VDE, 2021. VDE Normenbibliothek. Retrieved from. https://www.normenbibliothek.de/vde-xaveropp/normenbibliothek/static/login.
Veziroglu, T.N., 2007. 21st century's energy: hydrogen energy system. In: Sheffield, J.W., Sheffield, Ç. (Eds.), Assessment of Hydrogen Energy for Sustainable Development, NATO Science for Peace and Security Series C: Environmental Security. Springer Netherlands, Dordrecht, pp. 9–31.
Vogel, R., Güttel, W.H., 2012. The dynamic capability view in strategic management: a bibliometric review. Int. J. Manag. Rev. https://doi.org/10.1111/ijmr.12000 n/a-n/a.

Wainer, J., Przibisczki de Oliveira, H., Anido, R., 2011. Patterns of bibliographic references in the ACM published papers. Inf. Process. Manag. 47 (1), 135–142. https://doi.org/10.1016/j.ipm.2010.07.002.

Watts, R.J., Porter, A.L., 1997. Innovation forecasting. Technol. Forecast. Soc. Chang. 56 (1), 25–47. https://doi.org/10.1016/s0040-1625(97)00050-4.

Web of Science, 2021. Retrieved from. https://www.webofscience.com/wos/woscc/basic-search.

Weiner, S.C., Fassbender, L.L., Blake, C., Aceves, S.M., Somerday, B.P., Ruiz, A., 2013. Web-based resources enhance hydrogen safety knowledge. Int. J. Hydrog. Energy 38 (18), 7583–7593. https://doi.org/10.1016/j.ijhydene.2012.07.028.

Wurster, R., Hof, E., 2020. The German hydrogen regulation, codes and standards roadmap. Int. J. Energy Res. 6 https://doi.org/10.1002/er.6249.

Yonoff, R.E., Ochoa, G.V., Cardenas-Escorcia, Y., Silva-Ortega, J.I., Meriño-Stand, L., 2019. Research trends in proton exchange membrane fuel cells during 2008–2018: a bibliometric analysis. Heliyon 5 (5), e01724. https://doi.org/10.1016/j.heliyon.2019.e01724.

Zhao, N., Liang, D., Meng, S., Li, X., 2020. Bibliometric and content analysis on emerging technologies of hydrogen production using microbial electrolysis cells. Int. J. Hydrog. Energy 45 (58), 33310–33324. https://doi.org/10.1016/j.ijhydene.2020.09.104.

Zi, A., Blind, K., 2015. Researchers'participation in standardisation: a case study from a public research institute in Germany. J. Technol. Transf. 40 (2), 346–360. https://doi.org/10.1007/s10961-014-9370-y.

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