frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 14 June 2023
DOI 10.3389/fenrg.2023.1162732

OPEN ACCESS

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RECEIVED 09 February 2023
ACCEPTED 30 May 2023
PUBLISHED 14 June 2023

CITATION
Lee WS (2023), What can accelerate technological convergence of hydrogen energy: a regional perspective.
Front. Energy Res. 11:1162732.
doi: 10.3389/fenrg.2023.1162732

What can accelerate technological convergence of hydrogen energy: a regional perspective

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Focusing on technological innovation and convergence is crucial for utilizing hydrogen energy, an emerging infrastructure area. This research paper analyzes the extent of technological capabilities in a region that could accelerate the occurrence of technological convergence in the fields related to hydrogen energy through the use of triadic patents, their citation information, and their regional information. The results of the Bayesian spatial model indicate that the active exchange of diverse original technologies could facilitate technological convergence in the region. On the other hand, it is difficult to achieve regional convergence with regard to radical technology. The findings could shed light on the establishment of an R&D strategy for hydrogen technologies. This study could contribute to the dissemination and utilization of hydrogen technologies for sustainable industrial development.

KEYWORDS

open innovation system, technological convergence, triadic patent, Besag–York–Mollie model, hydrogen energy

1 Introduction

Currently, the technological advancement of hydrogen is attracting the interest of researchers and practitioners (Lebrouhi et al., 2022). Hydrogen has been identified as an important candidate for decarbonization of various sectors as hydrogen could contribute to the emergence of renewable energy by reducing the use of fossil fuels (Cheng & Lee, 2022). A focus on technological innovations and convergences might be required to accelerate hydrogen research and enable industrial transitions (Lebrouhi et al., 2022). Therefore, it is important to systematically approach how to facilitate technological innovation in hydrogen-related areas, and one way could be technological convergences in the open innovation era. In recent decades, technologies have been exchanged and interacted globally under the open innovation system (Maskell & Malmberg, 1999; Chesbrough, 2003; Granstrand, 2010). As the interactions of technologies have increased more than ever, it could accelerate the evolution of technologies (Lee & Sohn, 2018). As a result, technological convergence has become a popular phenomenon (Lee et al., 2015), and much effort has been devoted to analyzing and predicting the patterns of technological convergence (Kodama, 1995; Curran & Leker, 2011; Karvonen & Kässi, 2013; Sohn et al., 2013; Kim et al., 2014; Lee et al., 2015; Lee and Sohn, 2018).

Interestingly, patterns of technological innovation and even convergence vary across regions according to the technological capability of a region (Boschma and Martin, 2007). Specifically, the technological capability of a region tends to closely associate with the technological progress in that region (Crescenzi et al., 2012; Fagerberg et al., 2014). The technological capabilities could indicate the knowledge base of a region, which can be an important aspect of the analysis of technological convergence (Binz et al., 2014; Fagerberg et al., 2014; Hajek et al., 2014; Vásquez-Urriago et al., 2016). For instance, infrastructure technologies, such as hydrogen energy, could be influenced by the technological capabilities of a region. Then, how would the convergence pattern of hydrogen-related technologies vary across regions? This study focuses on the relationship between the regional occurrence of technological convergence and the regional knowledge base with respect to hydrogen energy.

This study uses the Organization for Economic Cooperation and Development (OECD) database of triadic patents as of January 2021 (OECD, 2021). Based on OECD triadic patents, the technological convergence and technological exchanges are empirically measured from a regional perspective at the Nomenclature of Territorial Units for Statistics (NUTS) 3 and Territorial Level 3 (TL3) levels compiled by the OECD. NUTS 3 and TL3 are regional-level units that are regarded as small levels intended especially for specific diagnoses. Then, a Bayesian spatial model with integrated nested Laplace approximation (INLA) was applied to investigate how the regional occurrence of technological convergence is associated with regional knowledge base factors.

The results of this study could provide both empirical evidence and a theoretical contribution to deepen our understanding of the technological convergence of hydrogen-related fields from a regional perspective. Findings could indicate which factors, such as diversity or originality, could positively leverage the occurrence of technological convergence at a regional level. The remainder of this paper is organized as follows: Section 2 presents a review of previous studies on technological convergence and related research. Section 3 presents the research framework. Section 4 analyzes the regional occurrence of technological convergence. Based on the analytical results, Section 5 discusses the policy implications for accelerating regional technological convergence. Finally, Section 6 concludes the study.

2 Literature review and research questions

2.1 Hydrogen energy for zero-carbon transition

Hydrogen has been considered an energy source that can trigger the zero-carbon transition (Cheng & Lee, 2022). In particular, it is expected that hydrogen could certainly contribute to the global energy transition with a significant reduction in greenhouse gas emissions (Lebrouhi et al., 2022). As the energy transition could be based on renewable energy, hydrogen and its electrification have attracted the interest of researchers and practitioners in many ways. More efforts are needed to develop technological innovations and their applications in related fields (Cheng & Lee, 2022). Previous research has focused on technical and technological advances for efficient production, stable compression and transportation, and effective utilization of hydrogen (Lebrouhi et al., 2022).

However, although hydrogen seems promising, there is the problem of technological advancement (Hunt et al., 2022). The efficient production and effective use of hydrogen require more technological innovation. Huge efforts from governments, industries, and academia would be required to achieve a satisfactory level of technological innovation in hydrogen-related fields. This could lead to a large-scale, hydrogen-based industrial ecosystem. It is also expected that hydrogen could even enable the grand transition to the decarbonization roadmap (Cheng & Lee, 2022).

Hydrogen is currently considered a promising energy source for the zero-carbon economy. In order to accelerate the technological progress of hydrogen, it is necessary to systematically study the technological development of hydrogen and establish a strategy to generate technological innovations in hydrogen-related fields.

Recently, Ashari et al. (2023) conducted a bibliometric analysis of publications, patents, and standards to specifically understand the evolution of hydrogen technology. They examined the link between the knowledge and technology transfer channels and concluded that the hydrogen technological innovation system is currently experiencing its formative phase. Li et al. (2023) conducted a systematic review of hydrogen technology development and emphasized that it was necessary to have possible and specific pathways to a hydrogen-capable clean energy future. Particularly, they highlighted the economics of hydrogen supply and discussed strategic considerations.

2.2 Open innovation and technological convergence

Technological innovation (henceforth, TI) can be defined as the process of developing a new and unique technology that satisfies the market demand for technology or the need for new technology. Many debates and studies have been devoted to the efficient and effective pursuit of TI. Recently, open innovation systems have attracted considerable attention for their significant contribution to efficient innovation in all industries. An open innovation system allows direct transactions and exchanges of innovative technologies (Chesbrough, 2003; Hemmert, 2004; Tanaka et al., 2007; Granstrand, 2010). In an open innovation system, public entities, whether firms, research institutes, or governments, do not bear the entire risk of R&D, do not keep R&D results in-house, and do not pursue TI on their own but rather release results for broader and more intensive application. Through this technology appropriation, the pursuit of TI has gained momentum, and the leverage effects of such pursuit for society have expanded, as the benefits of innovative technologies are obtained without directly conducting R&D. Previous studies have verified the positive impact of such exploitation of external technology and knowledge on business performance (Huizingh, 2011; Kani & Motohashi, 2012).

This aspect of open innovation leads to the accelerated exchange of technology between different technological domains and contributes to technological convergence. Technological convergence (henceforth, TC) could occur when innovations emerge at the intersection of existing technologies (Lee et al., 2015). A new technological domain could be created through technological change (Karvonen and kässi, 2013). As Dosi and

Nelson (2010) suggested, technological change was widely considered an evolutionary process. The evolutionary theory of technological change (ETTC) explains that technological evolution could be defined as the process of technological change and development through interactions among technologies (Devezas, 2005). As technological evolution is a process of variation, selection, and retention (Geels, 2002), ETTC has been proposed and utilized as a theoretical framework to analyze such technological changes.

TC is currently regarded as the combination of multiple technological elements to create new technological fields (Kodama, 1995; Kim et al., 2014). Under the current circumstances, the mechanisms and patterns of converging technologies need to be systematically analyzed to formulate relevant strategies. More opportunities can be created for the multidisciplinary combination of innovative technologies, thereby promoting TC. From the neo-Schumpeterian perspective, multidisciplinary convergence creates opportunities for new technological innovations and provides competitive advantages for economic entities such as firms and governments (Allarakhia & Walsh, 2012). Then, the convergence of two or more different technologies can lead to innovation in new technological areas (Karvonen & Kässi, 2013; Suh & Sohn, 2015). Consequently, TC accelerates innovation by enabling cross-sectoral knowledge and new ways of combining technologies (Karvonen & Kässi, 2013).

2.3 Regional perspective on technological convergence

TC on hydrogen-related domains in an open innovation system could take different forms in different regions. Because hydrogen-related domains require facilities and regional capabilities (Lebrouhi et al., 2022), taking a regional perspective is important to understand the technological development of hydrogen. Furthermore, TC may eventually occur in many regions that possess technologies with regional knowledge bases. The technological activities of economic actors in each region are critical for innovation (Boschma and Martin, 2007). The emergence and exploitation of TC may vary across regions, as each region has its own strengths in specific technologies. The agglomeration economies of regions contribute to TI through knowledge spillovers (Glaeser et al., 1995). Because the exchange of innovative technologies can be accelerated in the open innovation system, a regional perspective may prove to be an effective means of broadening the understanding of TC. Such an approach could be considered a "spatial spillover" of TI to analyze the mechanism of TC and its diffusion in different regions (Cabrer-Borras & Serrano-Domingo, 2007).

In particular, the technological capabilities of a region that can generate TI are largely influenced by the regional knowledge base (Doloreux & Shearmur, 2012). The regional aspect has been considered important for the study of TI (Todtling & Kaufmann, 2001; Capello & Lenzi, 2015). Many approaches to TI have been proposed in terms of the regional knowledge base. Cabrer-Borras and Serrano-Domingo (2007) analyzed innovation-related regional patterns, exploring the regional dependence and evolution of innovative trends in Spain. They presented regional proximity based on market transactions as an important factor in explaining the spatial spillover effect, highlighting that a certain level of regional development is required to improve the effectiveness of R&D policies. Kwakkel et al. (2014) analyzed spatial data related to TI from different perspectives, with the aim of supporting decision-making. Müller and Ibert (2015) highlighted the importance of the community of practice in the innovation process and applied the aspect of spatial analysis to this concept. These attempts to explain the spatial perspective of TI are based on specific regions or technological fields.

More efforts are being made to understand the technological interaction between regions and within regions. Hajek et al. (2014) systematically analyzed the regional innovation system by visualizing the European case and found that knowledge-intensive regions have a positive effect on spatially close regions. Binz et al. (2014) presented the reasons for the importance of the spatial aspect in TI from the perspective of knowledge dynamics in the biotechnology sector. They provided analytical diagrams of the innovation process based on the spatial concept. Caragliu and Nijkamp (2014) analyzed spatial spillovers in terms of human capital and economic growth. They found that regional labor markets have positive spillovers from local markets and that spillovers are important for cooperation between regions. Sleuwaegen and Boiardi (2014) analyzed regional innovation systems in terms of creative workers in the region. They provided further empirical evidence on regional intelligence.

At the national level, numerous attempts have been made to establish regional approaches to TI and related policies (Crescenzi et al., 2012; Haakonsson et al., 2012). Autant-Bernard et al. (2013) analyzed the impact of regionalized knowledge spillovers on policymaking in Europe. Their results showed the significant function of regions in the pursuit of innovative policies and the importance of regional characteristics. Hammadou et al. (2014) conducted a country-by-country analysis of the determinants of government R&D spending from the perspective of spatial econometrics. They analyzed that despite geographical distance, strong interactions were observed in the R&D spending of countries with similar foreign trade or industrial patterns. Vásquez-Urriago et al. (2016) analyzed science and technology parks (STPs) as an important component of innovation policy. Using a much larger dataset than in previous studies, the authors found that such STPs and their locations can facilitate cooperation for innovation.

2.4 Research issues

In recent decades, the emergence of open innovation system has brought frequent technological interaction among domains and regions. TC may take different forms in different regions, and the technological characteristics might vary from region to region (Comin & Hobijn, 2009). Geography has been found to play an important role in the R&D process (Reuer & Lahiri, 2013; D'Este et al., 2012). As TC could occur with different patterns in different regions (Comin & Hobijn, 2009), R&D collaboration across regions is becoming increasingly important, especially for triggering the innovation of hydrogen technologies (Alnuaimi et al., 2012; Broekel, 2015; Cheng & Lee, 2022).

Hydrogen energy is an infrastructure technology that requires facilities and investments. Diverse domains participating in developing hydrogen energy and regions are closely associated with technological advancement. One could consider the perspective of TC and region when approaching hydrogen technologies. Therefore, this study focuses on three aspects of technological capabilities that could be associated with TC: technological features, degree of technological exchange, and technological adaptability from the regional perspective.

Technological features

Among the different technological aspects, technological features are considered based on the range of hydrogen technology-affiliated domains. Specifically, this study concerns technological features in a region, such as the diversity of technology, their technological boundaries, and the number of countries where these technologies are protected. Then, this study asks whether a region with a broader technological boundary has a higher regional incidence of TC, especially based on the IPC diversity of technologies, the size of the patent family, and the number of patent claims.

First, if there are more diverse technologies, there could be a higher possibility of TC (Lee et al., 2015). That research article suggested that technologies in a region consist of diverse fields, and examined how skewed different fields are in these hydrogen technologies. Diverse technologies provide the potential for convergence, and the degree of skewness of hydrogen technologies indicated how widely technologies could be used. Second, the present study considers the legally protected hydrogen-related technological boundary as the boundary of technological rights. In general, the wider the technological boundary, the higher the market value of the hydrogen technology. Third, the number of countries in which the technologies are legally patented is considered. Hydrogen is an infrastructure issue of national interest. Patenting technology in foreign patent offices is a strategic decision because it involves cost and effort.

Technological exchange

The technological exchange between regions is regarded as an important factor for generating TC, as the advancement of hydrogen-related technologies requires active interaction between different technological domains and different regions. With regard to this, the spillover of such accelerated technological exchange is known to promote further TI and convergence (Cabrer-Borras & Serrano-Domingo, 2007; Ko et al., 2014; Kwakkel et al., 2014). It is known to lead to collaborative R&D in the regional innovation system (Broekel, 2015). This study considers that a high degree of technological exchange can provide opportunities for converging hydrogen technologies and is likely to increase the technological proximity between regions, further contributing to the research collaboration and the pursuit of TI (D'Este et al., 2012).

Such technology exchange can provide a basis for regional technological capabilities and interactions between regions. In particular, the technological exchange between regions can be classified as either a flow into existing technology or a flow out of subsequent technology. The degree of utilization of existing technology can be indicated by the frequency of backward citations of patents in each region (Nemet & Johnson, 2012). Frequent and timely use of existing diverse technologies can increase technological exchange. Utilization of existing diverse technologies can generate new hydrogen-leveraged technologies. The degree of utilization by subsequent technologies indicates the direction of technological exchange and technological value (Harhoff et al., 2003; Gittelman, 2006; Blind et al., 2009; Harhoff & Wagner, 2009; Czarnitzki & Hottenrott, 2011; Fukugawa, 2012; Nemet & Johnson, 2012).

This research paper considers the reliance on existing public science and patented technologies, which may indicate that more complex and fundamental aspects of knowledge are used to accelerate high-quality technology (Narin et al., 1997). Furthermore, technologies and scientific knowledge flow in and out continuously, and such technological interaction needs to be understood systemically. Therefore, it is examined if TC could be associated with the degree of technological interaction between regions as follows: being cited by other patents, citing other patents, and citing non-patent literature.

Technological adaptability

The technological adaptability of a region is important to consider for achieving TI and indicating the possible opportunity for TC (Tuominen et al., 2004). The adaptation of new technologies is likely to occur with many applications (Wood, 2005). Where the technological interaction on hydrogen actively takes place within a range of technologies, the adaptation of diverse technologies to different regions becomes critical for TC. As adaptability means the ability to respond to change (Weigelt & Sarkar, 2012), regional adaptability could be important to consider when managing rapidly evolving technology (Hassink, 2010). Specifically, such technological adaptability could lead to different perspectives for pursuing TC.

As indicated by Hassink (2010), regional adaptability is understood in terms of lock-in and path dependence on technologies. Regarding lock-in, the study considers whether technologies are general to other technologies or not, and this research paper considers the generality and originality of technologies. Technological generality was proposed by Trajtenberg et al. (1997) and has been used to identify general-purpose technologies (Hall and Trajtenberg, 2004). Technological originality represents the breadth of technological fields on which the patent is based. Trajtenberg et al. (1997) proposed technological originality to explain knowledge diversification and stated that inventions that rely on many different sources of knowledge should be original results in terms of path dependence. This study considers the time-variant aspect of regional adaptability. Adaptability can also be understood as the speed of response to change (Weigelt & Sarkar, 2012). The radicality of technology has been proposed by Shane (2001). It can be measured as a time-invariant count of the number of IPC technology classes in which the patents cited by the given patent are classified, but in which the patent itself is not classified.

Overall, this study examines whether a region with higher technological features, degree of technological exchange, and technological adaptability has a higher regional occurrence of TC. The following section examines and analyzes the data and methods used to investigate these research issues.

3 Materials and methods

3.1 Data and variables

Many studies have explained the phenomenon of TC using patents as indicators of technological development and growth (Sen & Sharma, 2006; Dubaric et al., 2011; Han & Sohn, 2014). This study analyzed the Organization for Economic Cooperation and Development (OECD) database of triadic patents as of January 2021. The International Patent Classification (IPC) of triadic patents was used to define TC, and European Patent Office (EPO) citations of triadic patents were used to represent technological exchange. All EPO citations of triadic patents were used to identify the main regions of technological exchange involved in the corresponding TC. In addition, the OECD REGPAT database was used to match patents with applicants' addresses at the Nomenclature of Territorial Units for Statistics (NUTS) 3 and Territorial Level 3 (TL3) levels compiled by the OECD.

An analysis of patents and their IPCs is an effective way to analyze TC (Karvonen & Kässi, 2013). This study analyzed the regional occurrence of TC based on triadic patents, which are considered valuable (Baudery & Dumont, 2006). The study used the triadic patent database provided by the OECD as of January 2021 (OECD, 2021). In this study, TC was defined as patents having multiple IPCs at the seven-digit sub-class level. If there were more than two different IPCs for the same patent, we considered that this exhibited the phenomenon of TC. To define TC, we used the IPC definitions, as of January 2021, of corresponding patents. We assumed that the co-occurrence of the same patent in the IPC defined the occurrence of TC on each patent (Curran & Leker, 2011). Based on this definition of TC, we narrowed all triadic patents to only TC patents for our analysis.

The analysis included 1,594,886 triadic patent families (as of 2021). A patent family was defined as a set of identical patents filed in different countries for the simultaneous protection of the same invention in those countries. Related patents were grouped together as patent families. OECD triadic patents included triadic patent families that had sets of patents filed with the EPO and the Japan Patent Office (JPO) and registered with the United States Patent and Trademark Office (USPTO). Converting the triadic patent families to the number of patents filed with the EPO yielded a total of 1,850,124 patents.

Then, the patents were filtered to 37,058 patents on hydrogen, especially the production and electrification of energy with the following IPCs: H01M004, H01M008, H01M012, C10B053, C10J, E02B009, F03B, F03C, B63H019, F03G007, B60K006, B60W010, H01M010, H01G011, H02J003, and H02J009 based on the WIPO Green Inventory. Then, patents with multiple IPCs at the seven-digit subclass level were considered to represent TC. For example, if there were more than two different IPCs for the same patent, it was considered to represent TC. The IPC definitions, as of January 2021, of the corresponding patents were used to define TC. The co-occurrence of the same patent in the IPC defined the occurrence of TC for each patent (Curran & Leker, 2011). Based on this definition of TC, all triadic patents were narrowed to only those with TC for analysis. As a result, patents on hydrogen and related fields had 832,329 EPO citations, with 140,404 IPC codes analyzed based on EPO assignments.

To understand the regional occurrence of TC, this study used REGPAT, another database provided by the OECD. REGPAT is a regional database of patent applications that can match applicants' addresses with their patents. The addresses provided were matched at the NUTS 3 or TL3 level. Table 1 outlines the variables used in this study to process these data.

EPO patents were used to measure the technological characteristics of a region. As technological characteristics of a region, we used IPC-related variables, such as IP counts and IPC Theil diversity, and those were averaged per region. These variables can indicate how diverse a region's technologies are and how skewed they are (Gao et al., 2013; Leydesdorff et al., 2014; Lee and Sohn, 2018). In addition, the average family size and the average number of claims are considered to represent the technological breadth of a region (Harhoff et al., 2003; Petruzzelli et al., 2015). Patent claims have been widely used to indicate technological boundaries. Previous studies have suggested that a large number of claims can require a higher patent fee, which, in turn, can represent a high market value and broad technological boundary. The family size of a patent can usually indicate how many countries the patent is protected in. The family size is measured by the number of patent offices where a given invention is protected, and it is normalized with respect to the maximum value shown by other patents in the same cohort (OECD, 2021).

The degree of technological exchange can be examined in terms of both citing other technologies and being cited by other technologies. For being cited by other technologies, the current study considered the average number of forward citations at the regional level. The forward citations of triadic patents were measured by the European Patent Office, with a window of 5 years after publication for timeliness. Next, the average number of backward citations and non-patent literature (NPL) citations was considered. Backward citations can be used as a measure of technology flow (Nemet & Johnson, 2012). In this study, technology flow was defined as the degree of dependence on other technologies. According to Lanjouw and Schankerman (2001), backward citation can indicate that the technology refers to relatively well-developed technological areas. Also, NPL citation indicates that the technology has a high quality and makes a public scientific contribution to industrial technology (Narin et al., 1997). Sometimes, technology with NPL citations is considered to have more complex and fundamental knowledge (Cassiman et al., 2008). In this study, backward citations and NPL citations were based on EPO citations. These variables represent how the regional knowledge base depends on the previous technology and knowledge. The degree of technological exchange of each region is measured by calculating the closeness centrality of the citation network regrouped by region (D'Este et al., 2012).

Finally, the adaptability of the region's technologies was studied sequentially. It could be categorized into originality, generality, and radicality. The generality was proposed by Trajtenberg et al. (1997), and this study used the generality as a modification of the Hirchman–Herfinahl index proposed by the OECD (OECD, 2021). The forward citation and citing IPC were measured and normalized from 0 to 1. When the technology was widely cited, the generality was calculated close to 1. On the other hand, originality, proposed by Hall et al. (2001) and calculated by backward citation, works differently. Originality is reduced when the technology cites

TABLE 1 Research variables.

	Variable	Description	Reference
Dependent variable	Tech_conv	Number of technological convergences per region	Curran and Leker (2011)
Technological feature	IPC diversity	Average IPC Theil diversity of triadic patents by region	Leydesdorff et al. (2014), Suzuki and Kodama (2004)
	Family size	Average family size of triadic patents by region	Harhoff et al. (2003)
	Claim counts	Average claim count of triadic patents by region	Milanez et al. (2017), Petruzzelli et al. (2015)
Technological exchange	Forward	Average count of forward citations by region (as of 2017)	Czarnitzki & Hottenrott (2011), Nemet & Johnson (2012), Fukugawa (2012), Harhoff et al. (2003)
	Citation		
	Backward	Average count of backward citations by region	Nemet & Johnson (2012), Harhoff et al. (2003), Harhoff & Wagner (2009)
	Citation		
	NPL	Average count of NPL citations by region	Narin et al. (1997), Cassiman et al. (2008)
	Citation		
Technological adaptability	Generality	Average generality of triadic patents by region; OECD defined	OECD (2021), Trajtenberg et al. (1997)
	Originality	Average originality of triadic patents by region; OECD defined	OECD (2021), Hall et al. (2001)
	Radicalness	Average radicalness of triadic patents by region; OECD defined	OECD (2021), Shane (2001)

Because triadic patents with multiple IPCs are considered to represent the occurrence of TC, the number of these patents by region is considered the degree of TC per region. With respect to the regional knowledge base, the following aspects are considered: technological specificity, technological exchange, and technological adaptability.

different technologies. Finally, radicality indicates technological capability (Shane, 2001). It can measure the relative weight of each IPC in the cited patents. Its values are then normalized from 0 to 1. A higher degree of radicalness can indicate that the technology relies on more diversified technologies.

3.2 Methodology

To effectively analyze the regional occurrence of TC, important regions were primarily considered in terms of open innovation. Important regions involved in technological exchange were identified by mapping patent-related regions after obtaining a patent network based on all patent citations. The regional level used for mapping regions was NUTS 3 or TL3. Then, a Bayesian spatial model of Poisson response was applied. The Bayesian spatial model required the distance matrix between the regions detected in this study. Because the technological proximity between regions may be more important than the physical distance between regions, the technological distance was used for the analysis. Based on the patent citation in terms of regions, a technological similarity matrix was constructed based on the Jaccard similarity. The elements in this matrix were dichotomized and the diagonal was set to zero. The Jaccard similarity was employed to calculate patent similarity based on patent citations:

$$J\left(Citations\,of\,Patent_A, \text{Citations of } Patent_B\right), = \frac{\left|Citations\,of\,Patent_A \cap Citations\,of\,Patent_B\right|}{\left|Citations\,of\,Patent_A \cup Citations\,of\,Patent_B\right|}.$$

As expressed in equation (1), the Jaccard similarity of patent citations presents the degree of citations shared by patents A and B among the total citations of patents A and B. Citation similarities among patents were then mapped as similarities in the inter-regional technological exchange, and regional data related to TC were regrouped around the regions covered under NUTS 3.

Before building the model, all independent variables were scaled with mean and standard deviation.

The model in this study refers to a Bayesian spatial model using INLA, called the Besag–York–Mollie (BYM) model (Besag et al., 1991; Blangiardo et al., 2013). BYM is an intrinsic conditional autoregressive (iCAR) model used to model areal counts of events by region. It models with covariates and provides the linear effect for the covariate (Rue et al., 2009). The following description of BYM was largely based on Blangiardo and Cameletti (2015). For each region i, the number of technological convergences follows a Poisson distribution, and the number of triadic patents for each region acts as an offset for Poisson response. Among various structures, the intrinsic conditional autoregressive (iCAR) structure in the present study was based on Besag et al. (1991). The coefficient could be interpreted as, "What percentage does the independent variable increase the dependent variable?"

A Bayesian spatial model of Poisson response was applied to the regional data with INLA. The Bayesian approach with INLA has been widely adopted, especially in epidemiology and spatial analysis. This approach is particularly effective and easy to use to specify a hierarchical structure of data with spatial and/or temporal characteristics (Blangiardo & Cameletti, 2015). In particular, the data of this study were distributed in the region with diverse technological features. It was also necessary to include the interactions among regions. Thus, this study suggested that the Bayesian spatial model with INLA could fit with the occurrence of TC over regions.

Concerning the proposed model, the estimation of the model could be challenging due to the complicated aspects of the proposed model. Markov chain Monte Carlo (MCMC) is widely used to compute such a Bayesian model. However, due to the complexity of the model and the dimensions of the database, INLA has recently been developed as an alternative to MCMC (Blangiardo & Cameletti, 2015). The INLA approach is computationally efficient; it was developed for latent Gaussian models, with flexible support for models ranging from generalized linear mixed to spatial and spatiotemporal models (Blangiardo & Cameletti, 2015).

The following explanation for BYM is largely based on Blangiardo and Cameletti (2015). For each region i, the number of technological convergences, Y_i, follows a Poisson distribution with λ_i, the average number of technological convergences for each region i. λ_i can be defined in terms of the occurring rate of technological convergences per a triadic patent for each region i ρ_i and the number of triadic patents e_i for each region i. e_i acts as an offset, and the parameters in η_i can be interpreted on the log relative risk scale. Therefore, we assume the following:

$$Y_i \sim Poisson(\lambda_i),\ \ \lambda_i = e_i\rho_i,\ \ \log(\rho_i) = \eta_i.$$

Here, ρ_i is modeled through a linear predictor η_i for each region i.

$$\eta_i = log(\lambda_i) = b_0 + u_i + v_i.$$

Here, b_0 represents the intercept, quantifying the average outcome rate in all the regions. v_i indicates the area-specific effect. Another area-specific effect, u_i, represents a spatially structured effect.

Among various structures, the CAR structure considered here is based on Besag et al. (1991). As each area i can be characterized by a set of neighbors, $\mathcal{N}(i)$, among n entire regions, u_i is considered as the following random variable:

$$u_i\Big|\boldsymbol{u}_{-i} \sim Normal\left(\mu_i + \sum_{j=1}^{n} r_{ij}\left(u_i - u_j\right), s_i^2\right).$$

Here, μ_i is the mean for a region i and $s_i^2 = \sigma_u^2/\mathcal{N}_i$ is the variance for the same region ($\mathcal{N}_i = \#\mathcal{N}(i)$). r_{ij} indicates the spatial proximity among regions and can be calculated as $\phi \times W_{ij}$, where $W_{ij} = a_{ij}/\mathcal{N}_i$, a_{ij} is 1 if areas i and j are neighbors and 0 otherwise. Φ controls the properness of the distribution.

Considering W as the matrix of elements W_{ij} and $\boldsymbol{S} = \mathrm{diag}(s_1, \cdots, s_n)$, the proper CAR specification, u is a multivariate normal random variable with the covariance matrix $(\mathrm{I} - \phi\boldsymbol{W})^{-1}\boldsymbol{S}^2$:

$$\boldsymbol{u} \sim \mathrm{MVNormal}\left(\boldsymbol{\mu}, (\mathrm{I} - \phi\boldsymbol{W})^{-1}\boldsymbol{S}^2\right),$$

where $\boldsymbol{\mu} = \{\mu_1, \cdots, \mu_n\}$ is the mean vector and I is the identity matrix. Thus, the conditional distribution of $u_i|\boldsymbol{u}_{-i}$ is

$$u_i\Big|\boldsymbol{u}_{-i} \sim Normal\left(\mu_i + \phi\frac{1}{\mathcal{N}_i}\sum_{j=1}^{n} a_{ij}\left(u_i - u_j\right), s_i^2\right).$$

TABLE 2 Patents per hydrogen-related IPC.

IPC	# of patents	IPC	# of patents
H01M010	14,415	H02J009	816
H01M004	11,555	H01M012	642
H01M008	9,569	F03G007	541
B60W010	4,121	F03C	379
H02J003	2,479	C10B053	342
H01G011	1,542	E02B009	97
F03B	887	B63H019	25
C10J	850	B60K006	0

The aforementioned specification is not widely used due to the difficulty in estimating ϕ. A simplified version of the formulation can be obtained by setting $\phi = 1$, which leads to the following conditional distribution for u_i:

$$u_i\Big|\boldsymbol{u}_{-i} \sim Normal\left(\mu_i + \frac{1}{\mathcal{N}_i}\sum_{j=1}^{n} a_{ij}\left(u_i - u_j\right), s_i^2\right).$$

It is called intrinsic conditional autoregressive (iCAR), and the BYM model originated from the aforementioned specification combined with the exchangeable random effect in the linear formula for η_i. In order to include our predictors, η_i can be modified as

$$\eta_i = log(\lambda_i) = b_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \beta_3 x_{3i} + \beta_4 x_{4i} + \beta_5 x_{5i} + u_i + v_i,$$

and v_i is the unstructured residual modeled using exchangeability among all regions such that

$$v_i \sim Normal(0, \sigma_v^2).$$

u_i is modeled as a first-order intrinsic Gaussian Markov random field.

$$\pi(\mathrm{u}|\kappa_u) \propto \kappa_u^{\frac{n-1}{2}}\, exp\left(-\frac{\kappa_u}{2}\sum_{i\sim j}\left(u_i - u_j\right)^2\right) = \kappa_u^{\frac{n-1}{2}}\, exp\left(-\frac{\kappa_u}{2}\boldsymbol{u}^T\boldsymbol{R}\boldsymbol{u}\right).$$

Both u_i and v_i assume Gamma prior distribution, and inference is conducted using INLA. Further details on INLA can be found in Blangiardo and Cameletti (2015).

4 Results

4.1 Descriptive statistics

The integrated data can be constructed using EPO patent application IDs, which are the key values in all OECD triadic patent applications, EPO patent citations, and the REGPAT of triadic patents. First, the patents derived from the EPO citation data were matched to the corresponding triadic patents. The triadic patents were filtered to 37,058 patents on hydrogen production and electrification of energy based on IPCs, such as H01M004,

TABLE 3 Descriptive statistics (unit: region).

	Mean	*SD.*	*Min*	*25%*	*Median*	*75%*	*Max*
Number of convergences	57.6122	424.4391	0	2.0000	4.0000	13.0000	7330.0000
IPC Theil diversity	0.0261	0.0579	0	0.0000	0.0000	0.0283	0.4112
Family size	7.2158	3.4877	3	5.0000	6.0000	8.2820	29.0000
Claims counts	14.7228	8.4582	3	10.0000	12.6358	16.9286	72.0000
Backward citations	5.7331	2.8510	0	4.0000	5.2500	7.0000	20.0000
NPL citations	0.8171	1.8985	0	0.0000	0.1824	1.0000	27.0000
Forward citations	2.5188	4.8716	0	1.0000	2.0000	3.1139	95.0000
Generality	0.3889	0.2214	0	0.2334	0.4182	0.5645	0.8568
Originality	0.6876	0.1640	0	0.6162	0.7123	0.8009	0.9372
Radicalness	0.2405	0.1775	0	0.1190	0.2059	0.3382	1.0000

In the next subsection, the association is further investigated between the regional occurrence of TC and factors related to the regional knowledge base.

H01M008, H01M012, C10B053, C10J, E02B009, F03B, F03C, B63H019, F03G007, B60K006, B60W010, H01M010, H01G011, H02J003, and H02J009, according to WIPO Green Inventory. Table 2 shows the number of patents for each IPC. As shown in Table 2, more than half of the patents were distributed on H01M, and other IPCs, such as B60W, H02J, H01G, F03B, C10J, F03B, F03C, and F03G, also appeared, indicating hydrogen production and electrification of energy.

The important regions of technological exchange were identified from the patent citation network by matching TCs to corresponding regions. TCs were identified and matched to regions by linking them to the corresponding regional information. The identified regions were matched using NUTS 3 or TL3. This process resulted in 428 regions.

After all the data were mapped by region, the research variables were established based on these main regions of technological exchange. For obtaining the dependent variable, the patents on TC were summarized by the region of applicants at the level of NUTS 3 or TL3. Particularly, if a patent could be filed by two or more applicants, there may be more than one regional code for a patent. In such cases, the number of TCs for each region was adjusted by multiplying the number of convergent patents by the ratio of applicants associated with that region. Then, the number of convergent patents was calculated for each region. In addition, the standard scaling was, respectively, applied to each independent variable. The distribution of the variables is shown in Table 3, and the table does not include the mean and standard deviation due to the standard scaled values with the mean and standard deviation.

4.2 Results of the spatial model

The BYM model was applied to the 428 regional datasets. The dichotomized technological distance matrix was used for the application of BYM. It was also assumed that the Poisson distribution for the dependent variable was used instead of the Poisson distribution because our dependent variable had overdispersion. Based on the results, the resulting matrix was constructed with columns and rows consisting of each region reflected in the BYM model. In addition, the logarithm of the number of triadic patents of each region was considered as the offset. The BYM analysis was performed using the INLA package of open-source R, and Table 4 depicts the estimated parameters of the BYM model.

Table 5 also indicates the estimated coefficients from the BYM model. Findings suggested the important factors of a region that trigger the technological convergences associated with hydrogen.

From the results, it was observed that a diverse exchange of technologies with high originality could exert a positive influence on the convergence of hydrogen technologies. Specifically, IPC diversity, originality, and citation level had a positive influence on TC in hydrogen-related fields. Among these variables, originality, which was expected to be an important variable, was found to increase the regional occurrence of TC by 5.4685 times. Next, IPC diversity gave a 14.68% increase to TC on hydrogen-related domains. Forward citations, NPL citations, and backward citations of technological exchange also increased the regional TC by approximately 5%, 5%, and 2%, respectively.

On the other hand, variables such as family size, generality, and radicalness had a negative influence on regional TC. Generality and radicalness all seemed to have a positive effect on TC, but an unexpected result was obtained. Generality reduced regional TC by 65.1%. In addition, radicality could lead to less occurrence of TC in a region. As the radicality of a region's hydrogen-related technologies increased, the region was 23.89% less likely to be involved in the rate of TC. This finding indicated that radical technology that lacks originality might not contribute to the advancement of hydrogen technology.

5 Discussion

This study examined the regional occurrence of TC to further accelerate TI in hydrogen-related fields. Specifically, triadic patents, EPO triadic patent citations, and REGPAT were used for the analysis. The important regions for an open innovation system

TABLE 4 Parameter estimation.

Model hyperparameter	mean	Sd	0.05quant	0.5quant	0.95quant	Mode
Size of the binomial observations (1/overdispersion)	2441.0010	42700.0000	25.9440	221.5370	7135.5750	38.8370
Precision for id (iid component)	0.1640	0.0140	0.1410	0.1650	0.1860	0.1680
Precision for id (spatial component)	1850.0000	1850.0000	189.7050	1333.7390	5398.1820	347.7560

Deviance information criterion (DIC, saturated): 861.02.
Effective number of parameters: 411.97.
Watanabe–Akaike information criterion (WAIC): 2389.31.

TABLE 5 Fixed effects of BYM for the regional occurrence of technology convergence.

	Variable	Mean	Exponentiated mean	Std. Dev	0.05quant	0.5quant	0.95quant	Mode
Technological Feature	IPC Theil diversity	0.1370	1.1468	2.2480	−3.5700	0.1400	3.8340	0.1460
	Family size	−0.0600	0.9418	0.0370	−0.1210	−0.0600	0.0010	−0.0600
	Claims size	0.0000	1.0000	0.0160	−0.0260	0.0000	0.0260	0.0010
Technological Exchange	Backward citations	0.0240	1.0243	0.0480	−0.0560	0.0240	0.1030	0.0240
	NPL citations	0.0550	1.0565	0.0710	−0.0620	0.0560	0.1710	0.0560
	Forward citations	0.0570	1.0587	0.0260	0.0150	0.0570	0.0990	0.0570
Technological Adaptability	Generality	−1.0500	0.3499	0.5540	−1.9620	−1.0510	−0.1370	−1.0510
	Originality	1.6990	5.4685	0.9100	0.2010	1.6980	3.1990	1.6980
	Radicalness	−0.2720	0.7619	0.8590	−1.6880	−0.2710	1.1410	−0.2700

were selected on the basis of patent citations in order to identify the regions that play a predominant role in technological exchange between regions. Globally, 428 regions contributing to the open innovation system were selected, and a variety of relevant regional data were collected and organized. BYM was then applied to explore the relationships between the factors associated with technological characteristics and TC in hydrogen-related domains.

The results suggest that the convergence of hydrogen technologies can be promoted in a region where there is a high degree of originality, which can be regarded as a region-specific technology. On the other hand, if the technology is associated with a patent family, it is not positively associated with TC in a region. Furthermore, IPC diversity and citations of a region seem to be positively related to the TC of hydrogen. That is, a region with hydrogen technologies plays an important role for TC. It is necessary to design a policy to accelerate the technological exchange among regions to expect more TC. However, if a region is not focused on some technologies, it may be difficult for that region to be positively associated with TC. In addition, if a region has a technology that has a wide technological boundary, it seems to negatively influence TC.

From the perspective of adaptability for technological interaction, generality, radicality, and originality contradict each other for TC. It is expected that generality might negatively influence TC because it might make technologies ordinary. Radicality might hinder TC because it excessively raises the boundary for convergence with other technologies. Radical technology appears to have difficulty in positively influencing interactions with other technologies. However, it is likely to be mixed with other technologies based on its own technological context and boundary. The aforementioned results imply that the policy of promoting TC among regions must take into account the technological adaptability a region currently has.

This study is one of the first to analyze regionally driven TC with all triadic patents, especially for hydrogen-relevant technologies. Based on the results, it is expected that spatial dependence will be reflected in future government or business policies and strategies related to the regional innovation system, especially to promote TC. Furthermore, the results suggest the feasibility of policies to promote TC with a regional focus. By identifying areas of technology with geographical advantages, more detailed research could be conducted to extend the investigation to the analysis of TC and synergistic cooperation on interregional spillover linkages.

This study has several limitations. First, its geographical scope in the analysis of TC was set at the regional level of NUTS 3 or TL3, to the exclusion of more detailed or higher-level analysis. A more detailed geographical level should be addressed in a follow-up study. It is also necessary to examine the phenomenon of non-patented technology, and this is left for future research.

6 Conclusion

Currently, the innovation of hydrogen technology has become increasingly important to ensure continued growth and maintain a competitive advantage in the era of open innovation. It has been recognized that an effective way of achieving TI is embracing TC. In particular, the pursuit of TC is emerging in the field of hydrogen technology. This study attempted to examine how TC occurs differently in various regions within hydrogen technology. The findings present the results of a Bayesian spatial model that incorporates the factors that are associated with the convergence of hydrogen technology with other fields using the valuable triadic patent database and its associated regional data of patent applicants. The findings of this study indicate the need to build R&D regions by generating active interactions and maintaining the diversity of original hydrogen technologies. Furthermore, one could consider the regional aspect in policies and strategies to promote TC. It is expected that this study could contribute to further research on the regional approach to TC and the design of policies for a hydrogen-triggered, zero-carbon industrial ecosystem.

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found in: OECD Patents Database.

Author contributions

WL contributed to the conception and design of the study. WL organized the database and performed the statistical analysis. WL wrote the first draft of the manuscript, contributed to the manuscript revision, and read and approved the submitted version. The author contributed to the article and approved the submitted version.

Funding

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (RS-2022-00166781).

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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