Evaluating the TIS's knowledge production function using patent data: A multi-criteria approach applied to the technological bricks of the hydrogen storage

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Evaluating the TIS's knowledge production function using patent data: A multi-criteria approach applied to the technological bricks of the hydrogen storage

by

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Abstract

At the heart of the Technological Innovation Systems (TIS) approach is the knowledge production function. Its evaluation requires the study and characterization of the TIS knowledge base and its evolution. Although patents are often used to study this knowledge production function, current techniques for mobilizing these data can be improved. In this article, we propose to work in two directions. Firstly, most studies focus on a singular knowledge base associated with the focal TIS. However, the knowledge spaces associated with a technology are themselves plural, comprising a variety of constituent elements that must be considered separately. In this way, we have broken down the knowledge base required to develop the focal TIS into different technological building blocks. These building blocks have been classified according to three different levels of analysis: type of technological solution, challenges to be met and field of application. Secondly, most studies measure the knowledge production function by the number of patents applications. However, the sheer volume of patents is a biased indicator. A more comprehensive approach to patent analysis is recommended, based on cross-checking several indicators to ensure the accuracy of patent statistics. From this perspective, we evaluate three sets of patent indicators - persistence, commitment, and coherence - to determine, for each subset, whether there is a sufficient level of knowledge created to promote the development of the TIS. All in all, this article proposes a new method of multi-criteria analysis of the knowledge production function in four stages. The relevance and operability of this method is illustrated in the case of hydrogen storage TIS.

Keywords: Technological Innovation System, Knowledge production, Metrics, Patent, Hydrogen storage technologies.

JEL Codes: O33; O31; Q55

1. Introduction

The Technological Innovation Systems (TIS) approach is a valuable tool for analysing the innovation process, particularly in the context of emerging technologies within the clean-tech sector (Markard et al., 2012). The concept of TIS refers to a socio-technical system whose capacity to develop, or not, needs to be assessed (Bergek et al., 2008). The fundamental premise of this approach is that the development of a technology necessitates the establishment of a robust innovation system, a phenomenon predicated on six pivotal innovation-related processes, collectively termed "functions." Each function corresponds to a category of processes that exerts a positive or negative influence on the evolution and dissemination of the technology. Among these functions, the knowledge production function is frequently cited as a primary driver of technological advancement.

This function is closely related to the learning issue inherent in any innovation process. It concerns itself with the knowledge base of the TIS and how well it is performing in terms of the breadth and depth of that knowledge base (Bergek et al., 2008). The knowledge base required to support the development of TIS is diverse, encompassing both scientific and technical knowledge related to the technology itself, as well as knowledge about the means of producing this technology, marketing it, consumer preferences, and so forth. A variety of modes of knowledge production may be involved, including research and development activities or imitation (Suurs & Hekkert, 2009). The role of the knowledge production function in the development of a TIS is of paramount importance (Hekkert et al., 2007), given that knowledge represents the most fundamental resource for technological innovation (Lundvall, 1992). Furthermore, for some scholars, this function is the most crucial among the six, as evidenced by the findings of Kao et al. (2019) in the context of IoT technologies in the manufacturing industry.

The analytical challenge in examining this function is to determine whether the knowledge creation process is conducted in a way that eliminates technological uncertainties and barriers and expands the field of possibilities. In particular, an examination of knowledge creation activities, particularly those pertaining to technical knowledge, is required to ascertain whether these activities are conducted at an adequate level and whether they are directed towards the generation of novel knowledge that addresses the requirements associated with the development of the TIS. As posited by Hekkert et al. (2007), patenting intensity represents one of three principal indicators (alongside R&D investment and R&D projects) for the study of this function. A number of studies have implemented this recommendation, demonstrating the utility of these data for determining the generation of knowledge, the nature of the knowledge produced, and the actors responsible (Berg et al. 2019; Frigant et al. 2019).

Nevertheless, two avenues for improvement should be pursued in comparison to the most commonly used methods. Firstly, the majority of studies concentrate on the differentiation of a singular, overarching knowledge base associated with the focal TIS. However, the knowledge spaces associated with a technology are themselves plural, comprising a variety of constituent elements. These may include, for instance, components, processes, applications, and so forth. Secondly, the number of patent applications is typically employed as a measure of the extent of knowledge production. However, the sheer volume of patent applications is a biased indicator of inventive activity aimed at producing technical knowledge (de Rassenfosse et al., 2008). In light of the aforementioned considerations, it is recommended that a more comprehensive approach to patent analysis be adopted, based on cross-checking several patent indicators in order to ensure the accuracy and reliability of patent statistics.

This article examines these two perspectives for improvement by proposing a four-step method whose primary objective is to enhance the comprehension of patent data in order to evaluate the TIS knowledge production function. In order to illustrate our approach, we present an analysis of knowledge development in hydrogen storage technologies. Our quantitative analysis of 8,600 hydrogen storage patents demonstrates significant inequalities between the 22 technology bricks that comprise this TIS, despite the observation of patent applications for each of them. This demonstration illustrates the potential of our multi-criteria approach to provide a more comprehensive understanding of the functional dynamics of a TIS.

The paper is structured as follows. In section two, after presenting a synthesis of the works that mobilize the patent to study the TIS knowledge creation process, we expose the limitations of the current approaches to study this function. Section three presents a 4-step method to address the limitations identified in section one. In section four, we apply this method to the hydrogen storage TIS. The discussion section summarizes the contributions of our proposal and highlights its limitations.

2. Using patents to study the TIS’s production of knowledge function: synthesis of practices and limits

2.1. The use of patent data for analysing the TIS development of knowledge function

Patents are one of the most widely used data for studying innovation. The wealth of information contained in a patent, its worldwide availability and its widespread use among innovative actors make it an essential piece of data on innovation. It is therefore natural that the first "methodological" works on the Technological Innovation Systems approach, in particular Hekkert et al. (2007) and Bergek et al. (2008), mention the patent as a key data for the study of the knowledge production and diffusion function. Recently, patent statistics have been used to measure the knowledge production of the autonomous vehicle (Meng et al., 2019), second-generation biofuels (Furtado et al., 2020), building-integrated photovoltaics technologies (Vroon et al., 2021), the powertrain systems (Phirouzabadi et al., 2020).

Some works make a more sophisticated use of patents to study knowledge production. Berg et al (2019), by integrating the concept of technology cycle (Tushman and Rosenkopf, 1992), propose a method based on patent data to anticipate the emergence of technologies within a TIS. To do this, they propose two indicators: the Patent Trajectory and the Category Concentration indicator, using patent classification codes. The two indicators are interrelated: the first aims to evaluate the development (knowledge) dynamics of an innovation system; the second makes it possible to calculate the concentration rate of these developments on the various technologies studied. Studying the TIS of the Swedish steel industry, Kushnir et al. (2020) estimate the R&D intensity of the private players in the TIS based on the weight of this field in the total patents of the applicants in relation to their overall R&D budget. Phirouzabadi et al. (2020) quantified and qualified the cross dynamics in the knowledge creation processes of different powertrain technologies. Using Lotka-Volterra predation equations applied on patents filed between 1985 and 2016, they observe four modes of interaction between different technologies: parasitism, commensalism, amensalism, and neutralism. Seeking to bridge the gap between work on TIS and sectoral innovation systems (Malerba, 2002), Malhotra et al. (2019) focus on learning-by-interacting processes between different sectors that contribute to knowledge development and diffusion. Studying the wind turbine, solar PV and lithium-ion battery TISs, they construct an indicator of the level of technological opportunity in the different sectors by focusing on the most cited patents in the field and studying their distribution according to the sectors concerned. By coding these patents by experts, they also evaluate for each sector where these sources of opportunity are located: at the process or product level.

2.2. The main limitations of current research

Considering the works just cited as representative of current analysis practices, we identify two perspectives for improving the exploitation of patent data for the study of the TIS’s knowledge production function.

2.2.1. The study of a single knowledge base

Bergek (2019) regrets the lack of detail in the knowledge base studied: the majority of empirical works only consider a single and global knowledge base for the TIS under study. For example, among the set of references cited in Section 1.1, only Meng et al. (2019) and Ahn and Yoon (2020) made an effort to decompose the knowledge base. Although the complexity of knowledge bases varies, in most cases it is possible to decompose the focal technology into several homogeneous subsets, since in a TIS analysis a 'technology' can be defined more or less broadly. Different situations can be distinguished, including the following three examples.

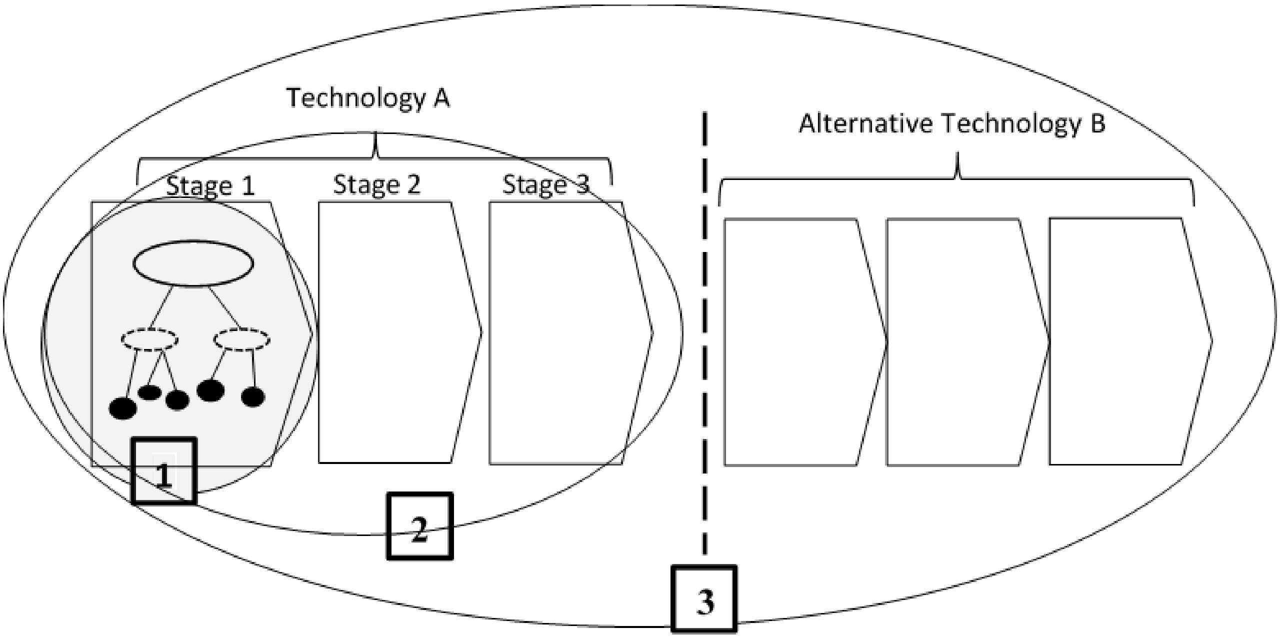
- First,, at a microscopic level, when the TIS is defined at the scale of a given technology (e.g. the heat pump (Kieft et al., 2021)), its knowledge base can generally be divided into several parts, since modern technologies are in themselves systems that integrate different components, which are then assembled into subsystems (Tushman and Rosenkopf, 1992) in a way determined by technology architectures (Henderson and Clark, 1990).
- Then, at a macroscopic level, a TIS can be defined as a technological field as a whole, a level chosen by König et al. (2018) on the TIS of aquaponics or by Suurs and Hekkert (2009) on that of biofuels. At this scale, several technological parts can again be isolated, except that they do not refer to a logic of interlocking but rather to a logic of competition. It is in this respect, for example, that Suurs and Hekkert (2009), in their study of the biofuels TIS, distinguish between first and second generation solutions and position the latter as an alternative to the former.
- Finally, at an intermediate level between the two preceding ones, a TIS can correspond to a technological value chain in accordance with Porter's proposal (2001), i.e. the set of complementary activities that contribute, from upstream to downstream, to the realization of a technology. Here, the decomposition of the TIS knowledge base corresponds to the successive stages of the value chain. It is in this perspective that Musiolik and Markard (2011) distinguished the value chain of Fuel cell technology for stationary application or Stephan et al, (2017) for lithium ion batteries.

As far as possible, it is desirable to try to study the knowledge base by differentiating its different parts, in order to reflect as faithfully as possible the reality of the diversity of knowledge sets that contribute to the production of the knowledge base. It is only by defining the knowledge base as precisely and realistically as possible that it is possible to really assess whether the various technical knowledge needs are being met, on which needs the actors have concentrated their efforts and, *a contrario*, to distinguish the missing spaces, understood as the virgin spaces likely to limit the development of the TIS.

Moreover, the decomposition of the knowledge base of a technological system is justified by the nature of the innovation process itself. In many cases, this process resembles a recombinant search, i.e. the combination of several known but different elements. The diversity of technological explorations is a factor of technological progress and, in particular, the knowledge development function is associated with the creation of a diversity of technological options (Suurs, Hekkert, 2009).

Figure 1. The multiple sources of "decomposability" of a TIS

1°TIS = a technology segmented into components and modules
2°TIS = a technological value chain spread over several stages
3°TIS = a technological field composed of alternative technologies



Source: Authors

2.2.2. The risk of misinterpreting patent data results

A second important limitation of the work using patents to study a TIS is that most of the work is based on the sole volumetric indication of the number of patents filed (over the timespan considered). However, although the patent is a classic indicator of inventive activity, it is widely recognized that it offers only an imperfect approximation, an issue which has been the subject of a large number of works, some of which are quite old (see for example Trajtenberg, 1987; Griliches, 1990).

It is important to note that the patent has several recognised limitations, one of which concerns the "false positives of patent statistics". This refers to the statistics of patent applications that could lead to the false belief that there is a high level of inventive activity in the field studied. There are two main origins of these false positives.

- The first issue concerns the utilisation of the patent system by inventive actors and the rationale behind patent applications. In recent decades, the patent system has been partially “diverted” by innovative actors, a phenomenon known as strategic patenting (Granstrand, 1999; Cohen et al., 2000; Blind et al., 2006, 2009; de Rassenfosse and Guellec, 2009; Veer and Jell, 2012). The result of this structural evolution is a trend towards a steady increase in the number of patents filed each year at the international level. Additionally, there is a growing demand for (and sometimes the granting of) patents on inventions that may not be strictly necessary. It should be noted that, when viewed in the context of a large group with a proactive property right policy and a yearly volume of several thousand patent applications, the filing of approximately ten patents on a technology over several years does not necessarily indicate a robust R&D strategy for that technology.
- The second reason pertains to the methodological aspects of building a patent analysis portfolio. The collection of patent data involves the selection of a specific subset from the vast array of existing patents. Nevertheless, formulating a strategy for querying a patent database pertinent to a specific technological object (such as a TIS) is a challenging undertaking in the absence of a clearly defined method that can guarantee the retrieval of all relevant patents in a given field (Trajtenberg 1987; Benson and Maguee, 2013). It is inevitable that patents which are not relevant to the subject matter will be included in the sample, even though this is not the intention.[1]

It is important to handle patenting statistics with care for both of the reasons outlined above. In addition to considering patent volumetric data, it is beneficial to employ a complementary set of patent indicators to cross-check and consolidate the information obtained. This is a crucial consideration when determining, as is the case in the TIS approach, whether there is sufficient knowledge production to ensure the development of an emerging technology.

3. Methodological proposals

This section presents a patent analysis method, structured in four steps (Figure 2), which overcomes the two main challenges previously identified when assessing the adequacy and alignment of inventive efforts with the knowledge base development needs.

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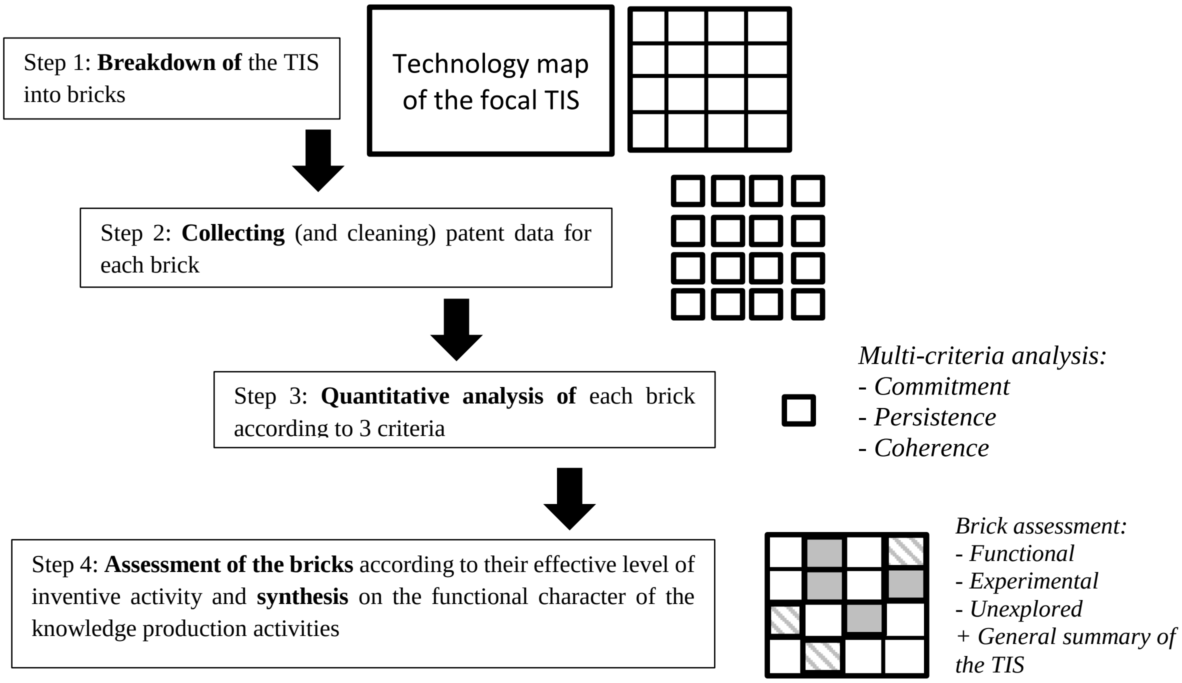
[1] In addition to false positives, there are also false negatives. These are patents that concern the technological object under study but are not captured by the elaborated query. This is due to a lack of adapted technical codes or a disparate vocabulary used by applicants. The issue of false negatives represents a challenge in terms of the comprehensiveness and depth of the patent analysis.

Figure 2. The four steps of the knowledge production function study



Step 1: Building a Technology Map

The initial stage of the process entails the creation of a comprehensive illustration of the knowledge base, with the objective of identifying the distinct sets that are necessary for the advancement, dissemination and utilisation of the technology in question. As previously indicated, the various categories of the technology map may encompass different types of elements, including the following: (1) the different technological components, (2) the types of technological solutions in the event of competition between different options, (3) technological constraints or challenges, and (4) the different registers of use or applications. The objective is to create a technology map, with the option of organizing it by level of detail when necessary.

The creation of this technology map requires technical knowledge that is more easily accessible by associating with an expert or through a thorough search of specialized articles and journals. Ideally, we recommend the first solution: the mobilization of a technical expert[2] in the field, as this person will be able to validate and enrich the results throughout the analysis.

Step 2: Patent data collection

The second step concerns the collection of patents relating to each component of the detailed technology map. This involves developing a patent query for each one, based on keywords and/or technical codes. Here again, interaction with an expert is required to validate the relevance of the queries developed and/or the patent portfolios collected.

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[2] This expert may be an engineer in a company operating in the sector, if the TRL is low, or a researcher in an academic laboratory.

Step 3: Calculations and statistics: Quantitative analysis of each brick based on the combination of three patent criteria

The third step consists in determining for each distinguished set of knowledge whether there is a real level of knowledge production or not. For the reasons mentioned above, the volume of patent filings being an insufficient indicator to rule on this question, we propose to base this evaluation on the association of three complementary criteria grounded on the TIS approach on the innovation.

- *Commitment*. The success of a technology is contingent upon the long-term commitment of a select few key players (Arora et al. 2004; Dosi et al. 1988), who are actively engaged in the introduction of a specific technology (Garud et al. 2010). The commitment criterion seeks to quantify the extent of inventive activity undertaken by a combination of three indicators. The first indicator corresponds to the total number of patents filed on the technological brick under study. To illustrate, a paucity of patents may be indicative of a lack of genuine inventive activity. The interpretation of this first indicator is rendered more precise when the structure of the total volume of patents is taken into account. Indeed, the degree of commitment is deemed to be high when specific actors invest considerably in a field where the overall number of patents is considerable. Depending on the sector in question, a variety of configurations are possible (Malerba, 2002), which leads us to consider two distinct indicators. The initial indicator is the proportion of patents held by the x principal applicants, specifically the top five and top ten (indicator 2: Concentration by main applicants). It is important to ensure that the applicants in question hold a significant share of the patents pertaining to the aforementioned brick and have managed to establish a significant position within the field. Furthermore, it may be beneficial to contextualise these statistics for each of the main applicants by evaluating the importance of their investments in this brick. This can be achieved by utilising indicator 3, which quantifies the weight of the brick on all the patents of the main applicants.
- *Persistence*. The objective of the second criterion is to deepen the commitment criterion through the consideration of patenting activity from a dynamic point of view. We try to determine whether or not they have been carried out over a significant period of time, or if on the contrary they are only the result of one-off efforts. This can be studied from indicators 4 and 5: respectively, the number of patents filed per year (of priority) on the whole of the knowledge brick studied, and for each of the main applicants.
- *Coherence*: We seek to determine whether the inventive activities have resulted in the development of "reference" knowledge, known and used by a significant number of innovative actors in the field. This criterion stems from the cumulative nature of the innovation process (Dosi 1982): each new invention is built on those that came before and, in turn, facilitates those that come after. The criterion of coherence is also found in another related function of TIS: the dissemination of knowledge. As Markard (2020) explains, after a period of technological diversity associated with uncertainty about the parameters to be taken into account, the development of a technology is accompanied by a clarification of expectations about the technology and a reduction in the diversity

of technologies. In the context of patents, this means the emergence of key patents and the presence of many pivotal patents that contribute to the diffusion of knowledge, and thus the knowledge production. In terms of patent analysis, patent citations can be used to gauge the coherence of inventive activities (Benson and Magee, 2015; Jaffe and de Rassenfosse, 2017). From these citations, several indicators can be calculated. We will consider the number of citations received by the most influential patents of the brick or the share of patents cited by the other patents of the same brick (indicator 6).

Step 4: Assessment of the bricks and global synthesis on the TIS

Based on the results obtained in the previous step, step 4 consists in classifying the technological bricks according to three categories that reflect a more or less strong level of technical knowledge production of the TIS.

- Level 1: "functional bricks" for which the knowledge production function can be considered fully functional.

  The patent statistics indicate a generally high level of overall patent filings (i1), and make it possible to identify several players who have sought to take a position on the development of technical solutions (i2, i3) through patent filings spread over a more or less long continuous period (i5). The innovation bricks have a trajectory: an upward or downward trend in patenting is observed (i4), but it is globally uninterrupted. A significant level of knowledge flows are observed between several patents (i6).

- Level 2: "experimental bricks": these technological bricks have been the subject of less inventive activity and therefore of patent filings than the functional ones (i1). The activity is rather sporadic (i4, i5) carried out by different actors without any of them having really succeeded in occupying a dominant position (i2, i3), each one having advanced independently without any significant knowledge flow between them (no or few key patents spotted) (i6). Here, the knowledge generation function is partially fulfilled and needs to be consolidated to support a positive evolution of the TIS.

- Level 3: "unexplored bricks": this category, the most critical, can be assimilated to unexplored spaces in the technological landscape of the TIS. There are holes in the knowledge base. Two cases correspond to unexplored: the technological bricks of the map for which no patent has been identified (i1) or those recording poor performance on the other criteria studied (i2, i3, i4, i5). On the basis of the patent statistics, due to the lack of a real level of inventive activity, the knowledge production function is not fulfilled and this is a blocking mechanism to the development of the TIS.

Table 1. Correspondence between patent indicators and brick categories

	UNEXPLORED	**EXPERIMENTAL**	**FUNCTIONAL**
	Low	→	*Strong*
Commitment			
(i1) Total number of patents in the brick	No or few patents	Average number (e.g. a few hundred)	Thick portfolio of patents (several thousand)
(i2) Concentration of patents on main applicants (i3) Weight of the brick for each of the x main applicants	Patents atomized among non-specialist applicants	No strong dominant position	Some key and/or specialized applicants
Persistence			
(i4) Temporal dynamics of global patent filings (i5) Temporal dynamics of main applicants	Weak and non-continuous patent filing dynamics	Unstable trend (intermittent between bullish and bearish dynamics) Peak patent filings concentrated in short periods for each applicant: one-off efforts	Identification of at least one long period (several years) of patent growth The main applicants show a continuity of inventive efforts
Coherence			
(i6) Number of citations received from main patents or share of patents cited by other patents in the same brick	No key patent identified and low citation flows between patents	Average share of patents influencing others	Several identified patents with a high level of impact on others or a high share of patents influencing others

4. An application of the method to hydrogen storage technologies

Hydrogen is likely to be a key component in the decarbonization pathways of many economies. According to CSIRO (2021), more than thirty major countries have published or are preparing a national hydrogen roadmap. The flagship reports by the International Energy Agency (IEA, 2021) or International Renewable Energy Agency (IRENA, 2023) state that hydrogen will be a key enabler to mitigate climate change and will also offer some opportunities to reshape the global geopolitical game of energy (IRENA, 2022). In particular, hydrogen appears to be a complementary solution for storing renewable energy production that suffers from alternative production (such as wind or solar power), while also appearing as a promising energy vector for mobility (cars, trucks, buses, planes, trains, boats).

However, we must not forget that this is not the first time that we have been sold the promises of hydrogen economy (Bockris, 2013). At the turn of the 2000s, this energy already appeared promising (Bakker, Budde, 2012). If the promises have not been kept, it is partly because storing and transporting hydrogen as an energy carrier is uniquely complex. As the lightest gas in the universe, hydrogen suffers from a very low volumetric energy density, despite having a very high gravimetric energy density. Put simply, you need extremely large volumes to store a small amount of energy. Therefore, if we hope to develop its use, storage seems to be the main obstacle to overcome. Many paths have been explored: liquid (i.e. cooled to -259.9 °C), compression, metals, alternative fluids such as ammonia... Each of these technologies has its own technical and economic limits, and a number of avenues have been opened, explored, closed and re-opened in each of these directions. The variety of solutions and actors involved (from companies to academic laboratories; from energy companies to users), combined with the societal challenge involved in the success of hydrogen, justify the choice of this case study to test the relevance of the proposed method for assessing the knowledge production function in its technological dimension.

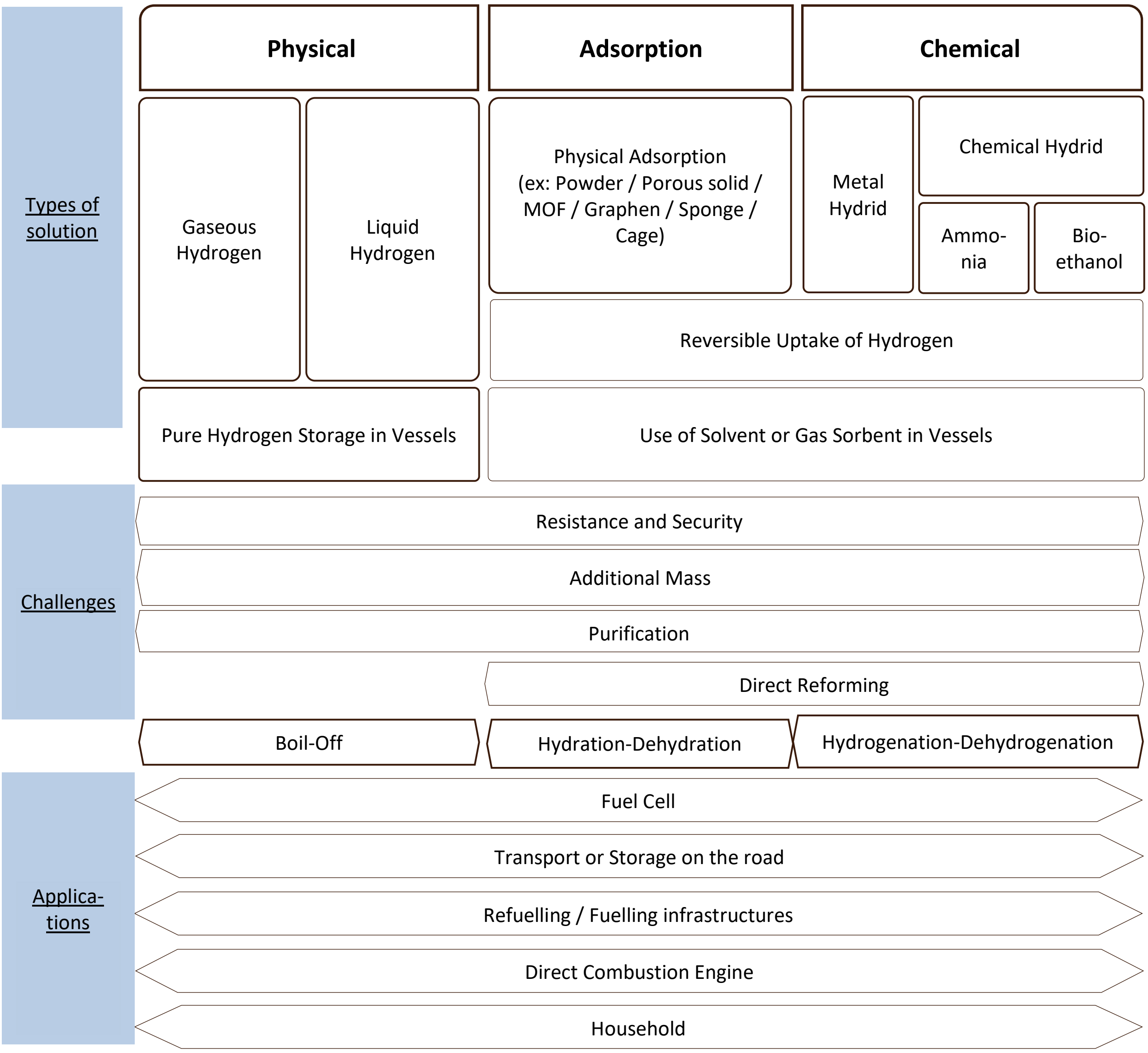
4.1. Step 1: Construction of a detailed hydrogen storage TIS map

The first step is to detail the TIS of hydrogen storage from a scientific and technological point of view. Technology reports can be used as a basis for this step, but the most appropriate method is to work with an expert in the field. For this project, we worked with an engineer from a major car manufacturer who is working on hydrogen storage. Collaboration with a scientific expert in the field has allowed the TIS hydrogen storage knowledge base to be broken down into 22 technological bricks divided into 3 levels (Figure 3).

1) The first level concerns technological solutions, of which there are three main families. The first is the physical solution: hydrogen is stored as gas or a liquid in pure molecular form without any significant physical or chemical bonding to other materials. The second is about molecular hydrogen be adsorbed onto or into a material, held by relatively weak physical van des Waals bonds. The last is atomic hydrogen chemically bounded. As each of the three families can be divided into a variable number of more precise subcategories, we have also taken these details into account, which makes it possible to distinguish a total of 10 technological solution bricks.

2) The second level refers to challenges in the field, which may or may not cut across several technological solutions. In all, there are seven barriers to current hydrogen storage solutions. Purification, since the purity of hydrogen is important for its use in fuel cells: a mixture of hydrogen with other chemical species and impurities leads to contamination of the fuel cell and degradation of its life and performance (Lamb et al., 2019). This is particularly true for the Polymer Electrolyte Membrane (PEM) fuel cell. Resistance and safety is another challenge for hydrogen storage TIS: all tanks for storing hydrogen in physical, adsorption or chemical form must be resistant and guarantee safe hydrogen storage. These criteria are essential, especially for mobility applications. Mass reduction is a key issue for on-board systems, which are required to be lighter and more compact. When hydrogen is used in liquid form, there is a specific blockage known as boil-off. Hydration and dehydration of hydrogen, processes that consume energy, correspond to another category of technological bottleneck, as do hydrogenation and dehydrogenation processes, mainly concerning the storage of hydrogen by adsorption or by chemical means.

Figure 3. Breakdown of the TIS of storage hydrogen into 22 bricks



Source: Authors

3) The third level is related to the five main applications of hydrogen storage technologies. The use of hydrogen in the home is mainly related to the production of electricity by fuel cells in stationary operation. These are Solid Oxide Fuel Cells (SOFC). This fuel cell technology has the advantage of using all forms of hydrogen storage, physical or chemical.

4.2. Step 2: Patent data collection and cleaning

The collection of patent data was carried out on the Orbit Intelligence database edited by Questel[3]. This database has several advantages: it offers an international coverage of patent offices and operates in terms of patent families (and not in terms of patent filings) in order to avoid counting several times the same patent filed in several countries. It also allows for a precise query of the textual fields of patents and/or the use of patent classification codes, in

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[3] https://www.questel.com/communication/news/news.html

particular the IPC (International Patent Classification) and the CPC (Cooperative Patent Classification[4]). Where appropriate, the two query options were combined to produce the most relevant patent corpus. Indeed, search strategies based on the use of keywords alone can be complex due to the multiple languages in which a patent is filed and the use of a disparate technical vocabulary. As for the classification codes, although they have the advantage of being harmonized and common to all the offices, they do not necessarily correspond to the desired level of search and may be too broad or too restrictive.

The patent data collection process was carried out in two stages. First, an initial global patent query was developed to delimit the knowledge base of the entire hydrogen storage TIS. Second, within this general boundary for each distinguished knowledge set, a patent query was formulated (See appendix). In all cases, the patent query was co-constructed and validated with the scientific expert according to an iterative process as advanced by Benson and Maguee (2013). On a sample of initially identified patents, the expert provided feedback to improve the relevance of the query by adding or removing query criteria. In total, for the global knowledge base of the TIS, we identified 9,130 patents filed over the period from January 2010 to May 2020. Among them, 8,600 (94%) could be attached to at least one of the 22 technology building blocks. Figure 4 presents the volumes of patents identified by each brick.

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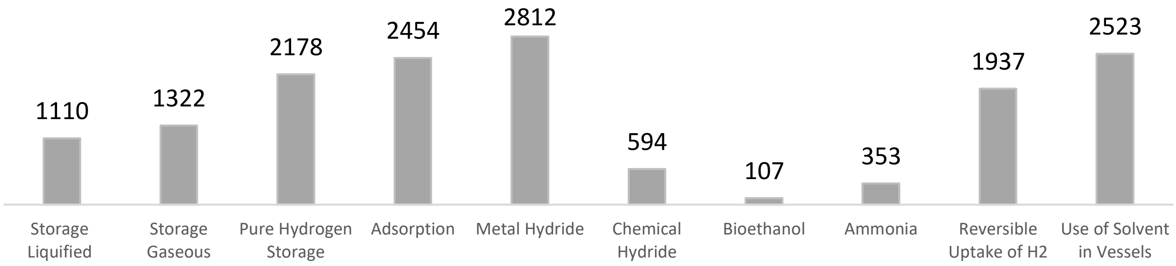
[4] https://www.wipo.int/classifications/ipc/fr and https://worldwide.espacenet.com/classification?locale=en_EP

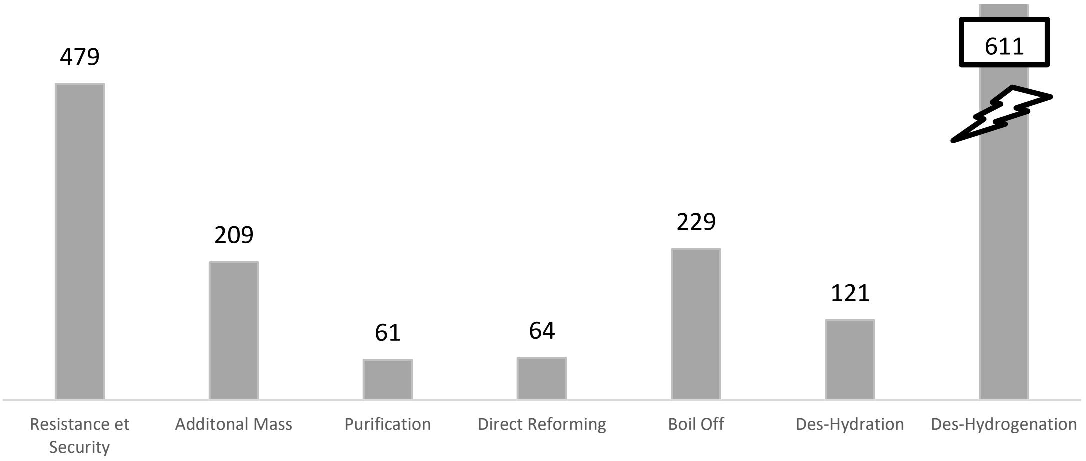
Figure 4. Overall level of patenting

Unit: Number of patents filed by brick, January 2010-May 2020

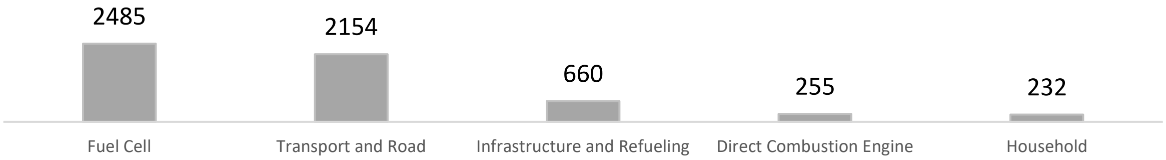
1- Types of solution



2- Challenges



3- Applications



Source: data Orbit, authors

4.3. Step 3: Calculate indicators for each technology subset

Each of the 22 patent portfolios thus discerned was individually studied according to the 3 sets of criteria commitment, persistence and coherence. Table 2 shows the main observations on the criteria of commitment and persistence. For coherence, in order to quantify the importance of intra-technology brick knowledge flows, we opted for the calculation of the percentage of patents cited by other patents belonging to the same brick (Table 3).

Table 2. Main observations based on the criteria of commitment and persistence

1) Types of technological solutions				
Gaseous	Liquid	Pure Hydrogen Storage in Vessels	Adsorption	Reversible Uptake of Hydrogen
- Steady growth in patent filings - The main applicants (Air Liquid, Toyota and BMW) hold between 9 and 7% of the patents, with uninterrupted patent filings since the early 2000s	- Rebound in patents over the recent period driven by BMW (13%) - AIR LIQUIDE and Linde, $2^{\text{ème}}$ and $3^{\text{ème}}$ filing with 8% maintain their deposits over the last decade	- Strong growth in patents since 2013 - BMW, AIR LIQUIDE, LINDE DAIMLER holding between 7% and 4% of the patents have increased their efforts over the recent period	- Unstable patent filing dynamics, ranging from 140 patents per year (in 2002) to nearly 60 (in 2012) - Toyota, the first applicant, holds 6% of the brick patents, followed by Panasonic and Honda (2% each). Their efforts are declining. - On the contrary, in the recent period, sudden positioning of isolated actors such as Tianjin University which protected more than 30 inventions in 2016	- Majority of patents filed in the 2000s, but maintained at over 50 patents annually - Toyota, the first applicant, holds 6% of the brick patents, followed by Honda (4%) and Intelligent Energy (2%). Their efforts are declining.
Metal hydride	Chemical hydride	Ammonia	Bioethanol	Use of Solvent or Gas Sorbent in Vessels
- The number of patents filed annually has been declining since the mid-2000s but has remained above 50 patents - Toyota, Sanyo Electric and Panasonic holds between 5 and 4% of the patents. The majority of the inventions are old, in particular they are before 2000 for Panasonic and Sanyo	- Global dynamics of patent filings on the decline, despite a rebound in 2016 - Low concentration of patents: BASF, 1^{er} applicant with 3% of patents has not filed any more patents over the last 10 years	- Most of the patents date from the 2000s, with an average of 20 patents per year - Intelligent Energy and Toyota have small portfolios of less than 20 inventions, each holding 5% of the patents	- With only 4 patents filed on an ad hoc basis, Honda and Toyota are the two main applicants in this field with a very low overall level of patent filings	- Even if the annual number of patents remains significant (more than 50 per year), the dynamic is rather decreasing - Toyota is the 1^{er} applicant with 9% of the patents, has considerably reduced its efforts. Honda, the second largest applicant with 4%, has virtually stopped filing patents.

<table>
<tr><th colspan="10"><i>2) Challenges</i></th></tr>
<tr><th colspan="2">Resistance and Security</th><th colspan="2">Additional Mass</th><th colspan="2">Purification</th><th colspan="2">Direct Reforming</th><th colspan="2">Boil-Off</th></tr>
<tr><td colspan="2">- The number of patent applications is increasing overall but remains low (below 50 per year)
- BMW has recently increased its efforts in this area and holds 9% of the patents, followed by Air Liquid (8%) and Daimler (6%)</td><td colspan="2">- Low level of patenting (about ten per year)
- Irregular patent filings by applicants.</td><td colspan="2">- Level of patenting is anecdotal
- No player has really protected an invention, Air Liquide being the most "prolific" player has 5 patents to its credit</td><td colspan="2">- Low and very irregular patenting
- No dominant position</td><td colspan="2">- BMW and Linde hold 13% and 9% of the patents respectively. Linde in particular has suddenly increased its efforts in the recent period
- The overall annual volume of patents filed remains nevertheless limited (only about twenty)</td></tr>
<tr><th colspan="4">Hydration-Dehydration</th><th colspan="6">Hydrogenation-Dehydrogenation</th></tr>
<tr><td colspan="4">- Low and very irregular patenting
- No applicant has built up a significant patent portfolio. Exxon Mobile is the leading applicant for patents filed 20 years ago</td><td colspan="6">- After a downward trend in patent filings, there has been a slight upturn in interest recently from new players
- Patent concentration is low, with Toyota and Seiku the main applicants holding 4% of patents each. They are no longer active</td></tr>
<tr><th colspan="10"><i>3) Applications</i></th></tr>
<tr><th colspan="2">Fuel cell</th><th colspan="2">Transport</th><th colspan="2">Refuelling / Fuelling</th><th colspan="2">Direct combustion engine</th><th colspan="2">Household</th></tr>
<tr><td colspan="2">- The number of patents is decreasing, but remains at correct volumes (>80 inventions)
- Toyota and Honda concentrate a significant share of the filings with 12% and 8% of the patents. The remainder is fairly scattered among the other players</td><td colspan="2">- A sharp increase in patents over the recent period, driven in particular by car manufacturers such as BMW, Daimler and Hyundai.
- Toyota and BMW, the two main applicants, hold respectively 9% and 8% of all patents</td><td colspan="2">- The number of patents is increasing overall, but remains at low levels
- Linde, Toyota and Honda each hold between 9% and 5% of patents. The latter two have a tendency to decrease their activities.</td><td colspan="2">- The number of patents is irregular and has never exceeded 20 patents filed in a year
- Toyota has built up the most significant patent portfolio by protecting some 30 inventions, which is nevertheless limited for such a firm, especially as these filings date from before the beginning of the 2000s</td><td colspan="2">- The number of patents is globally irregular and has never exceeded 20 patents filed in a year
- Air Liquide is the leading filer with 20 patents filed.</td></tr>
</table>

Table 3. Importance of intra-technology knowledge flows

Unit: Share of patents cited by other patents of the same brick

<table>
<tr><th colspan="7">1) Types of technological solutions</th></tr>
<tr><td colspan="2">Physics</td><td colspan="2" rowspan="3">Adsorption (51%)</td><td colspan="3">Chemical</td></tr>
<tr><td>Gaseous (63%)</td><td>Liquid (49%)</td><td rowspan="2">Metal hydride (58%)</td><td colspan="2">Chemical hydride (46%)</td></tr>
<tr><td colspan="2" rowspan="3">Pure Hydrogen Storage in Vessels (61%)</td><td>Ammonia (37%)</td><td>Bioethanol (13%)</td></tr>
<tr><td colspan="5">Reversible Uptake of Hydrogen (39%)</td></tr>
<tr><td colspan="5">Use of Solvent or Gas Sorbent in Vessels (57%)</td></tr>
<tr><th colspan="7">2) Challenges</th></tr>
<tr><td>Resistance and Security (45%)</td><td>Additional Mass (39%)</td><td>Purification (24%)</td><td>Direct Reforming (31%)</td><td>Boil-Off (35%)</td><td>Hydration-Dehydration (33%)</td><td>Hydrogenation-Dehydrogenation (42%)</td></tr>
<tr><th colspan="7">3) Applications</th></tr>
<tr><td>Fuel Cell (55%)</td><td colspan="2">Transport/ on the road (61%)</td><td colspan="2">Refuelling / Fuelling (51%)</td><td>Direct Combustion Engine (29%)</td><td>Household (30%)</td></tr>
</table>

Source: data Orbit, authors' calculations

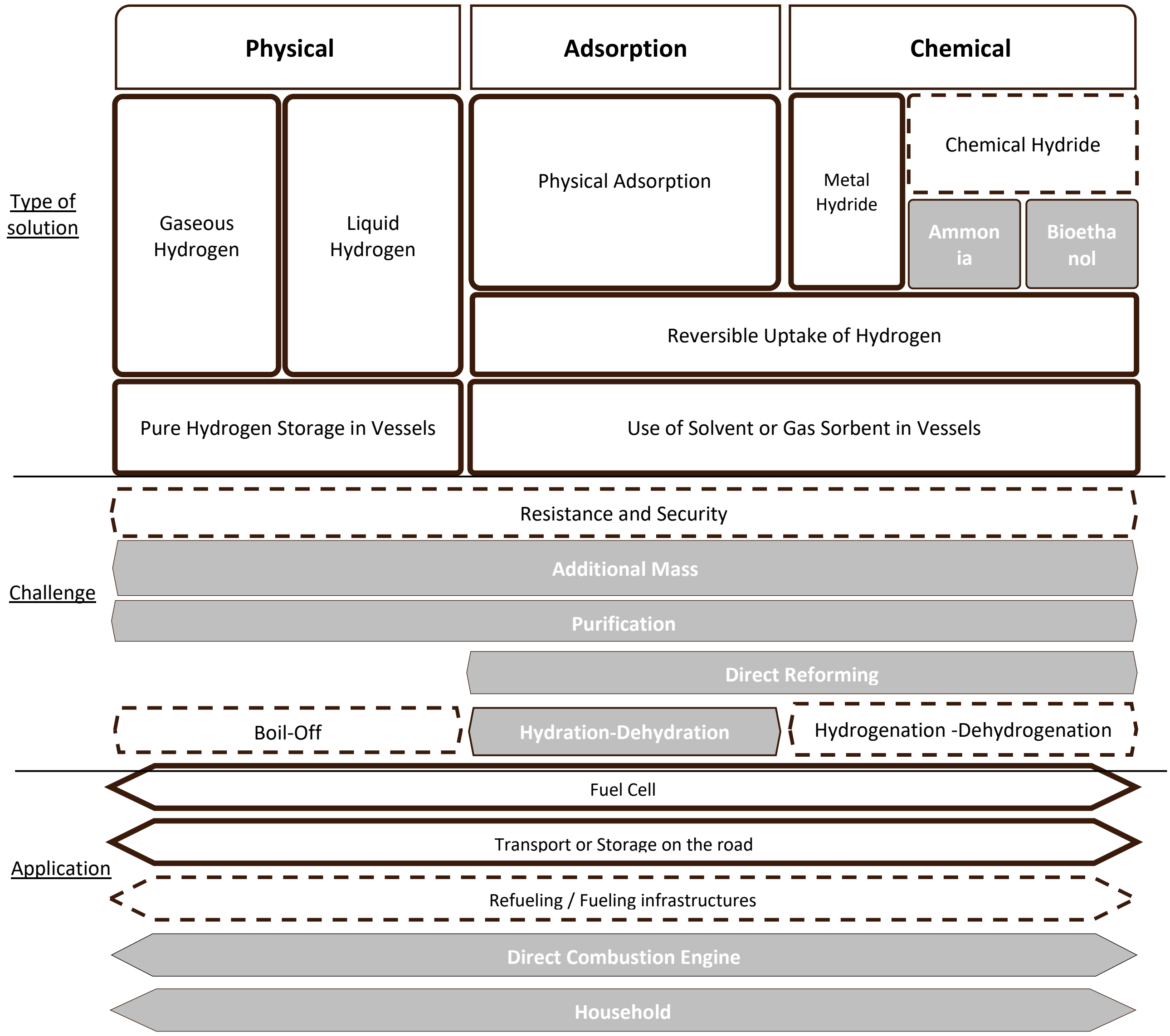
4.4. Step 4: Ranking of each part and overall evaluation of the TIS

In total, out of the 22 building blocks of the hydrogen storage TIS, the patent indicators allow us to consider that 9 are functional, 5 experimental and 8 unexplored. The breakdown is detailed below.

In terms of technological solutions, most of them are functional bricks. Adsorption and metal hydride solutions were the first to benefit from the R&D activities of the players, mainly Japanese players (Toyota in the lead for the two solutions, followed by Panasonic, Hitachi or Honda). Over the recent period, it is more at the level of hydrogen storage in pure physical form (gaseous hydrogen, liquid hydrogen and pure hydrogen storage) that the production of knowledge has been accentuated, mainly under the impulse of BMW. Of the three distinguished, the family of chemical solutions seems to be the least developed. Chemical hydride solutions are only at the experimental stage. There have been attempts, in the early 2000s, by Nissan and BASF, the two main players in this field. However, on the one hand, their efforts do not seem to have been pursued in a significant way, neither by these players nor by others. On the other hand, their position remains rather questionable since they each hold less than 3% of the patents. The situation seems even more problematic for ammonia and bioethanol-based solutions for which we do not observe any real knowledge creation efforts. It is worth noting that while we record no less than 300 patented inventions for ammonia (a non-negligible level), it appears from the patent statistics that the most prolific player (Intelligent Energy with 18 inventions) has concentrated the majority of its efforts in just one year (in 2012 with the protection of 8 inventions), which leads us to classify ammonia as a brick not really explored to date. This result echoes the fact that the use of ammonia as an energy carrier is a novelty (Makepeace et al., 2019; Chen et al., 2021; Malloupas et al., 2022).

It is at the level of technological barriers that knowledge production seems to be the least sustained to participate in the successful development of TIS. Concerns about the safety and resistance of these storage systems are currently the most important issues, followed by boil-off and hydrogenation. However, they can only be described as experiments due to the fact that they are only one-off efforts, concentrated over short periods of a few years. Mass addition, purification, direct reforming and hydration/dehydration show poor performance on the patent indicators studied, and are therefore unexplored parts according to our methodology.

Figure 4. Summary of results - classification of technology bricks by category



Functional part ▭
Experiments ⬚
Unexplored ▨

Source: authors

In terms of applications, two are functional: the production of knowledge on fuel cells, which seems to have been mainly driven by the efforts of Toyota and Honda in the 2000s, and the production of knowledge on road transport, which is also driven by car manufacturers, in particular BMW, which has consolidated its activities in the recent period. The (re)fuelling infrastructure is the next most important area, and should be classified as an experimental unit. Although Linde, Honda, Toyota and GM show a certain regularity in their patent filings, this is done at a low general level. Finally, regarding applications, household and direct combustion engine applications have not benefited from real knowledge creation activities. The volumes of identified patents are quite low (less than 20 registered per year); the portfolios constituted by the present actors are also quite marginal from a volumetric point of view and especially the patent activities are very irregular in time. These are gaps in the general knowledge base of the hydrogen storage TIS.

In summary, the application of our different sets of patent indicators suggests that the knowledge base of the hydrogen storage system is being built up in a very irregular way. Not all the knowledge sets with an impact on the development of this TIS are supported by genuine knowledge production activities.

5. Discussions and Conclusion

The objective of this article is to propose a method to better characterize the knowledge production function developed in the TIS framework from patent data. Indeed, most of the time, researchers studying this function either mobilize other methods (such as expert interviews, which have the drawback of limiting the analysis coverage), or evaluate the extent of knowledge production by reducing it to a question of the quantity of patents filed.

However, the volume of patents filed is not sufficient on its own to measure the dynamism of knowledge production in the TIS studied. The three proposed criteria – commitment, persistence and coherence – built around six indicators enable an in-depth analysis of this dynamic because they combine several points of view on the technology studied. These points of view refer both to elements of the quantity of recent and ongoing activities around the field, but also to the diversity of the actors involved, the consolidation of a technological consensus and key actors who are particularly active and militant for the technology. Before applying the criteria to the portfolio of patents collected, the article also argues for a more in-depth work on the definition of the focal TIS by reasoning both on the competing technological domains but above all by mobilizing experts to identify existing technical challenges and introducing reasoning about the technology's various possible fields of application. The idea is to build a technological map of the TIS that will help both to construct the patent application and to characterize the trajectory of knowledge creation in the field under study.

The analysis produced by this methodology enriches the characterization of the knowledge production function. Indeed, if the number of patents filed had been used to evaluate the production of knowledge in the field of hydrogen storage, it would have been very likely that the observers would have concluded that there was a positive and strong dynamic and would have been optimistic given the 9,000 patented inventions. Using this kind of volume counting, the European Patent Office recently published an optimistic report on the development of hydrogen in general (EPO/OECD/IEA, 2023), as did Bakker in 2010. An observer using the TIS analysis grid might then have concluded that this function was functional, and that there was therefore no need to encourage agents to increase their efforts (e.g. by funding demonstrators, research contracts, etc.). However, according to the proposed method, the feeling changes profoundly. Indeed, while agents are exploring the various technological solutions quite well, with the exception of chemical solutions, their efforts are rather disparate when it comes to tackling the main barriers blocking the development of concrete applications. Moreover, the efforts made are rather concentrated on certain fields of application, which weakens the hopes of a massive transition to a hydrogen economy (Rifkin, 2002), the horizon of which still seems distant as long as it remains complicated to store hydrogen massively, affordably and safely. In particular, the analysis shows that carmakers are currently very active. However, it is not clear that the avenues they are exploring open up useful general avenues for other uses. Furthermore, they themselves have to decide whether to bet on hypothetical future hydrogen-powered vehicles that are financially affordable, or to improve the performance of the electric vehicles already increasingly present on our roads. Evidence of reluctance and divergent individual choices was already apparent a decade ago in their divergent patenting behaviour (Flamand, 2016).

Thus, the twofold methodological proposal of this article (mapping different levels of knowledge and combine several analysis criteria on patent data) enables a finer analysis of the knowledge production function. For the work based on the TIS, this proposal should also enable to complete the range of empirical tools used to study this function. Indeed, it overcomes some of the shortcomings of patent databases while recovering some of the advantages of these data: worldwide coverage, possibility of identifying historical trajectories, identification of actors. In addition, the corpus of data constituted can be mobilized to study other aspects of the TIS. Thus, by focusing on co-patents, we can identify formal networks and thus highlight research communities, or even diverse influences (Frigant et al., 2019; Musiolik, Markard, 2011). Using citation trees, we can identify not only research communities but also, and above all, the way in which scientific trajectories are formed. (Epicoco et al., 2014), thus informing the Research Direction function of the TIS framework (Hekkert et al, 2007). However, while we argue that using patent data can be useful for describing and understanding how a TIS works if one seeks to construct indicators that are richer than simply counting patents or constructing simple citation networks, we do not argue that these data alone are sufficient to conduct empirical studies. Other methodological tools (expert interviews, analysis of grey or academic literature, etc.) and other types of databases (scientific, financial, etc.) are useful and necessary. The aim is to provide a complementary empirical analysis tool.

Moreover, the suggestions made in this article deserve to be developed further. A first step would be to test the ability of the methodology to travel to other cases of application in order to verify its relevance and, possibly, to improve the indicators selected. Working historically, i.e. ex post, rather than in vivo as we did, could provide a wealth of information, as Haupt et al. (2007) did for the study of pacemaker development. As an extension of this work, the three criteria used and the six indicators could be compared with other sets of indicators developed to study other issues, such as predicting which technologies will succeed. (Altuntas et al., 2015). A third avenue would be the exploration of whether other TIS's functions could be subject to similar methodological sophistication, whether with patent data or with other types of data. If, once again, we are advocates of mixed methods, the international and systematic dimension of the databases must serve to deepen the empirical approaches, certainly for the analysis of the knowledge production function proposed in this article, but also for the other five functions of the theory and the analysis of their interactions. This article will have achieved one of these goals if it succeeds in stimulating such work among our colleagues in innovation studies.

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Appendix. Patent query details

(Note: Codes, as in May 2020)

Stage 1: Global query

Codes CPC : Y02E60/321 OR Y02E60/322 OR Y02E60/324 OR Y02E60/325 OR Y02E60/327 OR Y02E60/328 OR Y02E60/32

Stage 2: Queries by levels

Type of solution

TYPE OF STORAGE BASE ON H2 PHASE
VESSELS FOR STORAGE
Codes CPC OR CIB: F17C*
PURE HYDROGEN STORAGE IN VESSELS
Codes CPC OR CIB: F17C2221/012
USE OF GAS-SOLVENTS OR GAS-SORBENTS IN VESSELS
Codes CPC OR CIB: F17C11*
GASEOUS HYDROGEN
Codes CPC OR CIB: F17C2223/0123 OR F17C2225/0123
LIQUID HYDROGEN
Codes CPC OR CIB: F17C2223/0153 OR F17C2223/0161 OR F17C2223/0169 OR F17C2223/013 OR F17C2225/0153 OR F17C2225/0161 OR F17C2225/0169 OR F17C2225/013
PHYSICAL ADSORPTION
Codes CPC OR CIB: C01B3/0015 OR C01B3/0021 OR C01B3/0084 OR Y02E60/325 OR B22F*
Concepts: TITLE/ ABSTRACT / CLAIMS: ADSORPTION OR (METAL ORGANIC FRAMEWORKS) OR MOF OR THF OR TETRAHYDROFURAN OR OXALANE OR POWDER* OR PARTICL* OR SPONGY OR GRAPHENE OR GRAPHANE OR FULLERENE OR NANOTUBES OR (CALCIUM CARBONATE) OR CLATHRATE OR CALIXARENES OR CYCLODEXTRINS OR ZEOLITES OR (GLASS CAPILARY ARRAYS) OR HGM OR (GLASS MICROSPHERES)
CHEMICAL ABSORPTION
Codes CPC OR CIB: B01D53/14* OR B01D53/148*
Concepts: TITLE/ ABSTRACT / CLAIMS: (Hydrog* absorpt*) OR (absorpt* hydrog*)

STATE OF THE STORED H2 / MEDIUM TO STORE
METAL HYDRIDES
Codes CPC OR CIB: C01B6+ OR Y02E60/327 OR C01B3/0026 OR C01B3/0031 OR C01B3/0036 OR C01B3/0042 OR C01B3/0047 OR C01B3/0052 OR C01B3/0057 OR C01B3/0063 OR C01B3/0068 OR C01B3/0073 OR C01B3/0078 OR C01B3/0084
Concepts: TITLE/ ABSTRACT / CLAIMS: (METAL* HYDRID*)
CHEMICAL HYDRIDES
Codes CPC OR CIB: Y02E60/328 OR C01B3/025 OR C01B3/04 OR C01B3/042 OR C01B3/045 OR C01B3/047
Concepts: TITLE/ ABSTRACT / CLAIMS: (Chemical hydrid*) OR (LIQUID ORGANIC HYDROGEN CARRIER) OR (LOHC) OR (LIQUID ORGANIC HYDROGEN) OR (HYDROGEN AND CARRIER) OR (LIQUID AND CARRIER)
AMMONIA
Codes CPC OR CIB: C01B3/025 OR C01B3/047 OR H01M8/222 OR Y02E60/364 OR C01C1/00
Concepts: TITLE/ ABSTRACT / CLAIMS: (NH3) OR (AMMONIA)

Concepts: TITLE/ ABSTRACT / CLAIMS: NOT "AMMONIA SOLUTION" OR "WATER" OR "AMMONIUM HYDROXIDE" OR "AMMONIACAL LIQUOR" OR "AMMONIA LIQUOR" OR "AQUA AMMONIA" OR "AQUEOUS AMMONIA“*(this sub-request eliminates ammonia)*
BIOETHANOL
Codes CPC OR CIB: C07C31/04 OR C07C31/08 OR H01M8/1011 OR H01M8/1013
Concepts: TITLE/ ABSTRACT / CLAIMS: (METHANOL) OR (ETHANOL) OR (BIOETHANOL)

Technological challenges

PURIFICATION
Codes CPC OR CIB: F17C2265/01*
RESISTANCE & SECURITY
Codes CPC OR CIB: F17C2260/011 OR F17C2260/042
ACTION SUR LE BOIL-OFF
Codes CPC OR CIB: F17C2265/03*
DEHYDRATION / HYDRATION
Concepts: TITLE/ ABSTRACT / CLAIMS: (hydrat* OR dehydrat*)
ADDITIONAL MASS
Codes CPC OR CIB: F17C2260/012
Concepts: TITLE/ ABSTRACT / CLAIMS: (Reduc* weight) OR (Reduc* mass) OR (limit* weight) OR (limit* mass)
HYDROGENTATION / DEHYDROGENATION
Codes CPC OR CIB: C07C5/3* OR C07C5/4* OR C07C5/5*
Concepts: TITLE/ ABSTRACT / CLAIMS: hydrogenat* OR dehydrogenat*
DIRECT REFORMING
Codes CPC OR CIB: H01M8/0618 OR H01M8/0637 OR Y02E60/566 OR C01B2203/067 OR C01B2203/0227
Concepts: TITLE/ ABSTRACT: (DIRECT REFORMING) OR (INTERNAL REFORMING) OR (ONBOARD REFORMING)
REVERSIBLE UPTAKE OF HYDROGEN
Codes CPC OR CIB: Y02E60/324

Applications

FUEL CELL
Codes CPC OR CIB: H01M8* OR Y02E60/50*
Concepts: TITLE/ ABSTRACT / CLAIMS : (Fuel cell) OR (PEMFC) OR (PROTON EXCHANGE MEMBRANE) OR (SOFC) OR (SOLID OXIDE) OR AFC OR (ALKALINE)
DIRECT HYDROGEN COMBUSTION ENGINE
Codes CPC OR CIB: F02M21* OR Y02T10/1* OR Y02T10/3* OR Y02T10/4* OR F02B2043/106
Concepts: TITLE/ ABSTRACT / CLAIMS : (Hydrog* engine)
REFUELING STATIONS / FUELING INFRASTRUCTURE
Codes CPC OR CIB: F17C2270/013*
Concepts: TITLE/ ABSTRACT / CLAIMS: (Fuel* station) OR (refuel*) OR (fuel supply*)
APPLICATIONS FOR FLUID TRANSPORT OR STORAGE ON THE ROAD
Codes CPC OR CIB: F17C2270/016* OR F17C2270/017* OR F17C2270/0181 OR F17C2270/0184
Concepts: TITLE/ ABSTRACT / CLAIMS: Vehicle OR truck OR Railway OR Bus OR Car
HOUSEHOLD
Codes CPC OR CIB: F17C2270/07*
Concepts: TITLE/ ABSTRACT / CLAIMS: HOME OR HOUSEHOLD