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Knowledge production in technological innovation system: A comprehensive evaluation using a multi-criteria framework based on patent data—a case study on hydrogen storage

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ABSTRACT

Knowledge production activity is central within a technological innovation system. The number of patent applications is commonly used to evaluate this activity. However, it is subject to bias and inaccurate evaluations can occur. This article proposes a multi-criteria framework based on seven complementary patent indicators, taking into account the persistence, commitment, and coherence of knowledge production activities for a more comprehensive evaluation. We demonstrate the value of our proposal through a case study on hydrogen storage, comparing patent data since 2000 about three technological solutions: physical, chemical and adsorption technologies. Our framework clearly shows that physical hydrogen storage is the most advanced in terms of knowledge production, despite not having the highest number of patent applications.

1. Introduction

The Technological Innovation Systems (TIS) approach is useful for studying the innovation process, especially when it comes to emerging technologies in clean-tech sectors [1]. The notion of TIS refers to a sociotechnical system that enables the development and diffusion of a new technology [2]. The key idea is that the development of a technology requires the construction of a strong innovation system, a phenomenon based on six key innovation-related processes called "functions". Each function corresponds to a category of activities that positively or negatively influences the development of the technology. Among these functions, one of the first commonly mentioned is knowledge production.

This function, which is closely related to the learning issue inherent in any innovation process, is concerned with the knowledge base of the TIS and how well it is performing in terms of the breadth and depth of that knowledge base [2]. The knowledge that needs to be produced to support the development of TIS is diverse: it includes both scientific and technical knowledge, but also knowledge about the means of producing this technology, marketing it, consumer preferences, etc. Several modes of knowledge production can be involved, including R&D activities or imitation [3]. The knowledge production function plays a key role in the development of a TIS [4], since knowledge is the most fundamental resource for technological innovation [5]. Moreover, for some scholars, this function is the most important among the six, as [6] showed for the case 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 removes technological uncertainties and barriers and expands the field of possibilities. Specifically, this means looking at knowledge creation activities to determine whether these activities are conducted at a sufficient level and whether they are aimed at creating new knowledge that meets the needs associated with the development of the TIS. In this respect [4], have suggested that patent is one of the three main indicators (along with R&D investment and R&D projects) useful for studying this function. Several works have implemented this recommendation, showing that this data is relevant for determining whether knowledge is created, what kind of knowledge, and by which actors [7].

The number of patent applications is generally used to quantify the level of knowledge production. But we know that it's a biased indicator of inventive activity aimed at producing technical knowledge [8]. Raw data on the number of patent filings is generally used to quantify the level of knowledge production. However, we know that this is a biased indicator of knowledge production for multiple reasons, including the fact that not all patent filings are of equal value—some will result in granted rights, while others will not even be examined. Moreover,

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innovative actors have unequal capacities to file patents; some invest significant time and money in building large portfolios of marginal or even useless patents. For all these reasons, relying solely on the number of patent filings can provide a distorted picture of the actual investment made by inventive actors in producing knowledge. The main risk being an overestimation of this investment.

The aim of this article is to propose a multi-criteria framework designed to extract deeper insights from patent data and provide a more comprehensive evaluation of knowledge production activity. Our framework focuses on three key criteria: commitment, persistence, and coherence in the knowledge production process and combines 7 easy-to-use indicators. To demonstrate the practical application of our framework, we are conducting a case study within the TIS of hydrogen storage, comparing three technological solutions: chemical, physical and by adsorption. The quantitative analysis of almost 9200 hydrogen storage patents shows strong inequalities between the 3 solutions, and demonstrates that our approach can provide a more relevant understanding of the TIS's knowledge production function.

The paper is structured as follows. In Section Two, following a synthesis of the works that mobilise the patent to study the TIS knowledge creation process, we expose the limitations of the current approaches. Section Three presents a four-step method integrating our multi-criteria framework to address the limitations identified in Section Two. 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 current practices and limits

2.1. The use of patent data for the assessment of the knowledge production function

In their seminal article presenting the TIS [2,4], explain that there are several methods for evaluating the knowledge production function. The overarching principle is to examine the dynamism of knowledge creation and to ascertain the depth and breadth of the knowledge base that should facilitate the emergence of the focal technology. The fundamental premise is that the prerequisite for the advancement of a technology is the accumulation of knowledge. Within the systemic framework of this approach, the diverse forms of knowledge, including scientific, technological, market, and organizational, must be examined. This multifaceted nature of knowledge allows for an extensive range of data sources to be utilized: scientific publications, R&D projects, number of professors, and number of patents [2: p.415].

Amongst these various categories of data, patents occupy a particularly significant position. By analysing patent data, researchers can gauge the output of innovative activities within a specific technological domain. The frequency and nature of patents filed can indicate the intensity of research and development efforts, the collaboration between different actors in the innovation system, and the commercial potential of new technologies. Furthermore, patents offer insights into the diffusion of knowledge, as they often reference prior art, revealing networks of innovation and the cumulative nature of technological progress. Additionally, patent databases are global and well-structured, thereby facilitating the evaluation of knowledge production on a worldwide scale.

By mobilising patent data, the analyst is able to ascertain which entities are engaged in the production of knowledge and to what extent, as well as the precise nature of that knowledge. This is achieved by examining the specifics of the claims, the parties involved, and the geographical location, whether global or regional. This approach permits the quantification of the extent of knowledge production and the characterization of its genesis. Accordingly, in recent years, a large number of authors have employed patent data from a TIS perspective to examine the knowledge production function in a variety of domains, including autonomous vehicles [9], second-generation biofuels [10], second-generation biorefineries [11] and, building-integrated photovoltaic technologies [12].

Although the majority of these studies concentrate on quantifying the knowledge-building blocks developed over time, and/or propose an analysis of networks of players (e.g. Ref. [7]), other studies put forward more sophisticated analyses. For instance Ref. [13], quantified and qualified the cross dynamics in the knowledge creation processes of different powertrain technologies by using Lotka-Volterra predation equations applied on patents filed between 1985 and 2016 [14]. focused on learning-by-interacting processes between different sectors -wind turbine, solar PV and lithium-ion battery-that contribute to knowledge development and diffusion. Others seek to combine the analysis of patent data with other data sources. To illustrate [15], incorporated R&D expenditure to study the Swedish steel industry and [16] employed a database integration approach, combining publications, patents and standards, to examine the dissemination of knowledge and technology within the hydrogen TIS.

2.2. Limitations of existing approaches

Although this work has enhanced the analytical toolkit for examining the knowledge production function, it is important to note that the majority of these studies rely on a single volumetric indicator: the number of patents filed. Although patents are regarded as a hallmark of inventive output, it is widely established that they provide only an imperfect representation of knowledge development. This shortcoming has been the subject of extensive scholarly inquiry, with numerous studies providing evidence to support this claim (see, for example, [17–19]).

Among all the recognized limitations of the patent, the one worth mentioning here concerns the "false positives of patent statistics". By this expression, we designate the statistics of patent filings which could lead to the false belief that there is a high level of inventive activity in the field studied. These false positives have two main origins.

The first is related to the practices of use of the patent system by the inventive actors and to the reasons for filing patents. Over the last few decades, the patent system has been partly "diverted" by innovative actors, which is qualified as strategic patenting [20–25]. 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, but also the demand for (and sometimes the granting of) patents on inventions deemed unnecessary. To be clear, for example on the scale of a large firm with a proactive property right policy and proceeding each year with several thousand patent applications, the filing of about ten patents on a technology in several years does not necessarily indicate a solid R&D activity on this technology.

The second reason is related to the methodological aspects of building a patent analysis portfolio. The collection of patent data implies the constitution of a delimited sample in the vast set of existing patents. However, developing a patent query relevant to a particular technological object is not an easy exercise in the absence of a well-defined method that would deliver with certainty all the patents in a given field, and only those [17,26,27]. Patents not appropriate to the object of study are unintentionally but systematically collected along with "good" patents.[1]

For both of these reasons, it is appropriate to handle patenting statistics with care and to seek to go beyond patent volumetric alone by making use of a complementary set of patent indicators to cross-check

[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 the lack of adapted technical codes or a disparate vocabulary used by the applicants. False negatives present a challenge in terms of the coverage and exhaustiveness of the patent analysis.

and consolidate the information obtained. This is particularly important to consider when deciding, as is the case in the TIS approach, whether or not there is a sufficient level of knowledge production to ensure the development of an emerging technology. However, this does not mean that the patent loses all its relevance for assessing the knowledge production function and its dynamics. On the contrary, patents remain a rich source of information, but several pieces of information have to be extracted simultaneously. For these reasons, we defend the use of a multi-criteria framework based on patent data.

3. Methodological proposals

In this section, we propose a patent analysis method, structured in four steps and integrating several criteria, which has the main advantage of avoiding the pitfalls previously exposed when we seek to determine whether the knowledge production is carried out at a sufficient level for the development of a TIS.

Step 1: Building a Technology Map

The first step consists in drawing a detailed representation of the knowledge base to identify the different sets needed for the development, diffusion and use of the technology. The primary objective of this initial phase is to gain an understanding of the different technologies, their similarities and their differences in terms of knowledge.

The creation of this 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 is to collate patents pertaining to each component of the technology map. This necessitates the formulation of a patent query for each component, based on keywords and/or technical codes. Once more, input from an expert is essential to validate the relevance of the queries developed and/or the patent portfolios collected.

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 set of knowledge whether there is a real level of knowledge production or not. For the reasons mentioned above, the volume of patent is an insufficient indicator to rule on this question. Thus, we propose to base this evaluation on the association of three complementary criteria grounded on the TIS approach.

- *Commitment.* Research on the economics of innovation has shown that the success of a technology depends on the involvement of key actors [28,29] who actively work towards the development of this technology [30]. From this perspective, the commitment criterion aims to assess the level of inventive activity undertaken, based on the study of three indicators. Following [10–13,31], we consider the number of patent applications as a way to measure the knowledge production function. Thus, the first indicator corresponds to the total number of patents filed on the technological field under consideration (indicator 1: total number of patents). As a preliminary illustration, an "abnormally" low number of patents may be deemed sufficient to negate the assumption of real inventive activity. To illustrate, if the study period encompasses several years on an international scale, a count of only a few dozen protected inventions on a worldwide scale is insufficient to conclude that there is any meaningful inventive activity. The interpretation of this first indicator becomes more precise when we take into account the structure of this total volume of patents. In fact, the degree of commitment is high when certain actors invest particularly in a field where there are a large number of patents overall. Depending on the sector, different configurations are possible [14], which leads us to consider two indicators. The first one corresponds to the share of patents held by the *x* main applicants (indicator 2: concentration rate for top applicants). The stake here is to ensure that applicants hold a significant share of patents of the field studied and have managed to establish a significant position in the field. Another favourable situation can be envisaged: a moderate or low concentration rate may be offset by the presence of specialized applicants, that is, entities dedicating the majority of their R&D activities to the development of the technology under study. These are typically technology start-ups that possess specific expertise and therefore play a particular role in advancing the studied technology. We recommend calculating a specialization index, as the proportion of an applicant's patents related to the technology under study relative to its total number of patents across all technologies (indicator 3: specialization rate).
- *Persistence.* The aim of the second criterion is to look at patenting activity from a dynamic point of view. We try to determine whether efforts to develop knowledge in the field span over a significant period or whether, on the contrary, they are the result of sporadic efforts. There are two ways of looking at this kind of regularity in knowledge production activity. The first is to look at the continuity of effort over time by key actors. This involves taking a microeconomic approach to the portfolio to check whether the main applicants are investing in the technology over the long term. The underlying assumption is that if patents do indeed reveal the knowledge base developed by firms [32], then a regular flow of patent applications reflects a deepening of the knowledge base in the field. In order to gauge the continuity of patent application activities of the main applicants, we propose as Indicator 4 to identify number of applicants applying patents in the technology for a minimum of 10 consecutive years over the past 20 years. Another way of looking at this notion of persistence is to examine the applicant's patent management strategy and in particular the renewal of their patents. Since applicants have to pay fees to maintain their property rights over time, whether or not they want to keep their patents alive is a good indication of the value they place on them [33,34]. It can therefore be inferred that when an actor renews a patent, it does so because it considers the underlying knowledge base to be worth maintaining. We proposed a simple indicator (indicator 5) which consists of calculating the part of patent still alive at the time of analysis for the main applicants in the technology field under consideration.
- *Coherence.* The third criterion aims to assess whether inventive activities were conducted in a relatively effective manner, resulting in the creation of "reference" knowledge that is recognized and utilized by a significant number of innovative actors in the field. This criterion is derived from the cumulative nature of the innovation process [29]. Within the realm of intellectual property rights, this phenomenon is reflected in the emergence of key patents that are valuable and significantly influence other patents, serving as reference points for the accumulation of knowledge. The coherence of inventive activity can be evaluated through patent citations. We recommend using forward citations, as this is one of the simplest and most effective methods for gaining insights into the technological impact of the patented invention [35,36] or knowledge flows [37,38]. For greater precision, we suggest considering only citations from patents within the same technological field to avoid including impacts on the development of knowledge in unrelated technology areas (Indicator 6: number of forward citations from patents within the field).

[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.

Additionally, analysing citation flows between main applicants can provide valuable insights into the emergence of knowledge communities and the proximity of R&D activities among them—two indicators of a robust knowledge base. A straightforward approach to evaluate this is to represent citation flows between applicants in network form and calculate the density of this network. This density is determined by the number of applicants connected to another relative to the total number of considered applicants (Indicator 7).

Step 4: Comparison of technological solutions and overall assessment

The final stage of the process is to consider all criterions in combination in order to facilitate an evaluation of the extent to which the knowledge production function is performing and how it is performing. In the event of multiple technological avenues being in competition with one another, this step allows for the ranking of the technologies in question in relation to one another. One advantage of the multi-criteria approach, apart from enriching the perspectives by multiplying them on the knowledge development function, is that it also enables the identification of any weaknesses in the technology and so the points to improve. It's particularly important since a technology may be the subject of a large number of patent applications, yet the production of knowledge does not appear to be sufficiently structured to allow the emergence of a real process of knowledge accumulation.

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. The flagship reports by the International Energy Agency [39] or International Renewable Energy Agency [40] 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 [41]. A recent article studying the volume of patents confirms this strong interest on the part of the automotive industry, and Japanese carmakers in particular [42].

However, we must not forget that this is not the first time that we have been sold the promises of hydrogen economy [43]. At the turn of the 2000s, this energy already appeared promising [44]. If the promises have not been kept, it is partly because storing and transporting hydrogen as an energy carrier is 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 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 stakes 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. The existence of different technological paths will enable us to use our method to compare the knowledge development functions of the three technologies that emerge from step 1.

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

There are a number of potential technological avenues that could be pursued for storing hydrogen. We collaborated with a European automotive industry engineer to delineate principal technological solutions, each comprising several sub-pathways. These pathways are founded on disparate domains of scientific and technological knowledge, justifying their distinction.

The three technological solutions are physical, absorption and chemical (for further details, please see Ref. [45]). In the physical solution, hydrogen is stored as a gas or liquid in its pure molecular form, without any significant physical or chemical bonding to other materials. In the absorption solution, molecular hydrogen is physically adsorbed on the surfaces of solid materials via van der Waals bonding. Subsequently, the hydrogen is released through the application of thermal stimulation or an alternative suitable method. Examples of these solid materials include activated carbon, zeolites, carbon fibres, and so forth. The last is the chemical solution, where the atomic hydrogen reacts chemically with solids to form hydrides, such as metal, complex and chemical hydrides. The main advantage of these pathways is their high energy density. However, this technological solution requires a dual process of hydrogenation and dehydrogenation that is not yet fully mature, particularly in the case of metal hybrides.

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] which enables the collection of patented inventions (in patent families) on an international scale. For each storage hydrogen solution, a patent query was formulated based on key-words or patent codes from the IPC (International Patent Classification) and CPC (Cooperative Patent Classification) (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 Ref. [28]. On a sample of initially identified patents, the expert provided feedback to improve the relevance of the query by adding or removing query criteria.

4.3. Step 3: calculate indicators for each technology subset

For each of the three technologies, we applied our multi-criteria framework to evaluate the development of the knowledge base.

4.3.1. Commitment

A preliminary examination of the patent applications reveals that the three technological solutions are the subject of a significant number of patent applications. This seems to indicate that the three solutions are the focus of significant knowledge development based on this volumetric analysis of the filings alone. According to this criterion, the absorption solution appears to have been the most extensively studied, with 4120 families, followed by the physical pathway with 3717 families and then the chemical pathway with 3537 families.

The annual evolution of patent applications for the three technologies shows a general upward trend over the past two decades (Fig. 1). However, notable differences in trajectories deserve attention. The filing dynamics appear more cyclical for chemical and adsorption technologies, while physical technology has seen a continuous increase. Also, the latter reached a peak in 2020 with 385 protected inventions, but the patent filing activity has significantly declined since then, which is not the case for the other two storage technologies.

A comparative analysis of patent concentration rates among leading applicants reveals a notable concentration in physical storage technologies (Table 1). In this domain, the top five applicants collectively hold 28 % of patents, compared to "only" 9 % for adsorption and 7 % for chemical technology. This disparity is also evident when the top 10 or 30

[3] Orbit intelligence is a worldwide patent database. More than 100 million patents are integrated and patent offices representing more than 99.7 % of the World's patent applications are covered in the database. To date, more than 97 % of our collection is in English, native or pre-translated, allowing for a wider and more comprehensive search. The FamPat database is Questel's world patent database grouped by invention-based families. For more details, please see https://www.questel.com/communication/news/news.html.

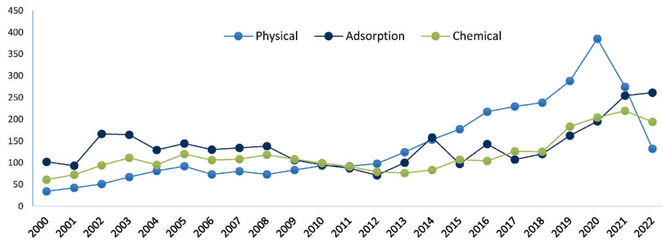

Fig. 1. Temporal evolution of patent application (Unit: Number of patent family by priority year).

Table 1
Patent concentration rate of top applicants.

	Adsorption	Physical	Chemical
Top 5	9 %	28 %	8 %
Top 10	14 %	37 %	12 %
Top 30	25 %	49 %	25 %

leading applicants are considered (indicator 2).

Notably, several automotive manufacturers have made substantial efforts to build extensive patent portfolios in physical solutions. BMW leads with over 320 protected inventions, followed by Toyota with approximately 200, and Honda with around 100 (Fig. 3). In contrast, for the other two technologies, Toyota, the main patent applicant, has filed smaller portfolios: 150 patent families for adsorption and about 60 for chemical technology (Fig. 2 and 4).

In terms of specialization (we consider a specialized actor as one who applied at least one-third of their patents on the studied technology), it would appear that only chemical technology benefits from the activities of such specialized actors (Fig. 4). Examples include Ovonic Battery, which has nearly 40 % of its patents in this area. Acquired by BASF in 2012, Ovonic Battery developed a metal hydride storage device that absorbs hydrogen in a manner similar to a sponge absorbing water. Other specialized actors are Vodik Labs, with 80 % of its patents related to disruptive solid-state hydrogen storage technologies with high energy density, and Hydrogenous LOHC Technologies, a German company also holding 80 % of its patents in chemical storage.

4.3.2. Persistence

The strong positions of leading applicants in physical storage have been achieved through consistent patent filings over time. Among the top 30 applicants, 9 organizations have been active for at least 10 consecutive years over the past two decades (2001–2021) in this technology (indicator 4 – Figs. 5, 6 and 7). This number drops to only 4 actors for chemical storage and 3 for adsorption. Notably, the activity of several applicants is particularly concentrated in a few years or even just one year for adsorption. For instance, Shanghai Huapeng Explosion-proof Technology Co., a security science and technology corporation, filed all 53 of its patents in 2014, while Tanjin University filed about thirty patent families in 2016, with no resulting patents granted.

The status of patent applications, in particular their lifespan, provides insight into the persistence of innovation (indicator 5 – Table 2). In the context of physical storage, the indicators are particularly favourable. Currently, 65 % of patents in this field are active, either still under examination or granted and maintained, compared to 40 % for chemical storage and only 29 % for adsorption. A clear example of this difference is illustrated by Toyota, which is involved in all three technologies and maintains 75 % of its patents for physical storage (the majority of which are granted and maintained). In contrast, only 12 % of its adsorption patents and 11 % of its chemical patents are still in force. With regard to physical storage, it can be observed that the majority of actors maintain their patents. However, there are a few exceptions, including Linde, Daimler, and Chicago Bridge & Iron, which have lapsed their patents. With regard to the field of adsorption, only a small number of companies, including Hyundai Motor and China Petroleum Chemical, continue to actively manage their patents. In contrast, the situation in the domain of chemical storage is more complex. While they represent a minority, a greater number of companies have elected to retain their patents in force, relative to those in the adsorption technology. This includes General Research Institute for Non-Ferrous Metals, Korea Institute of Science & Technology, China Petroleum & Chemical, and Hydrogenious LOHC Technologies.

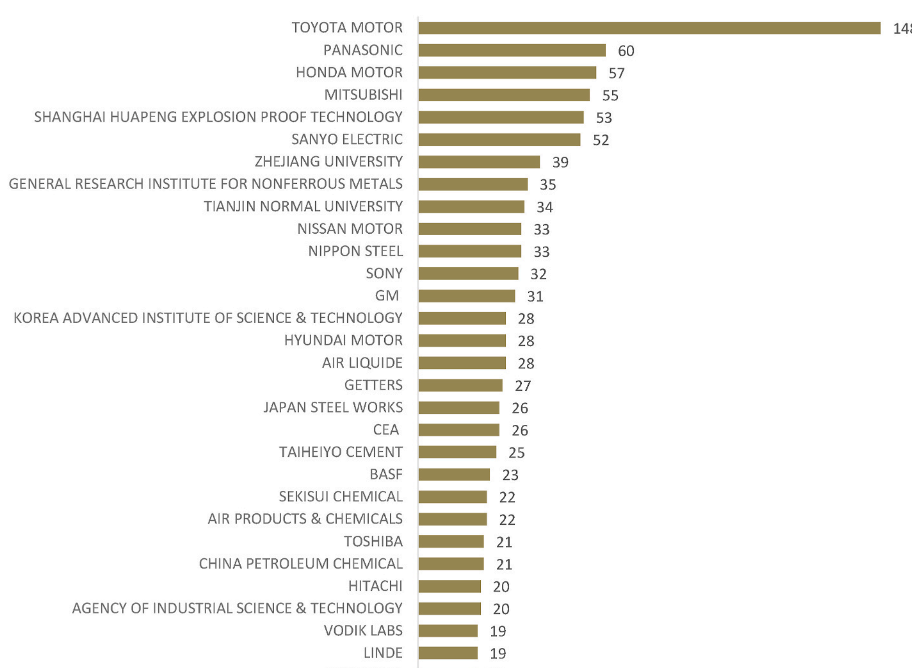

Fig. 2. Top 30 applicants in absorption storage technology (Unit: number of patent family).

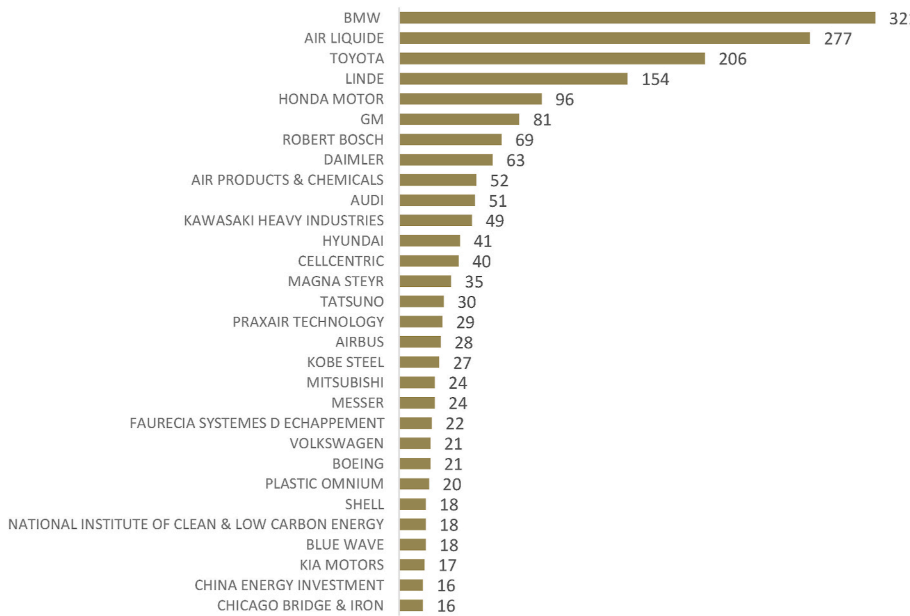

Fig. 3. Top 30 applicants in physical storage technology (Unit: number of patent family).
Note: In blue, specialized actors that have filed at least one-third of their patents on the studied technology.

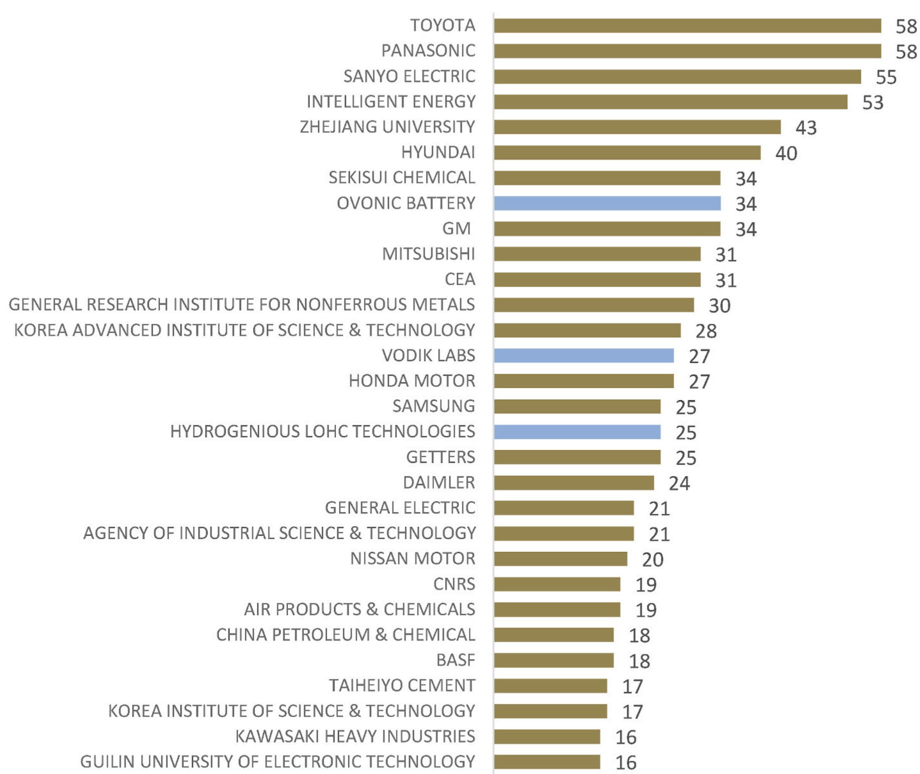

Fig. 4. Top 30 applicants in chemical storage technology (Unit: number of patent family).

4.3.3. *Coherence*

The pursuit of a robust knowledge base also appears to favour physical storage technology. An analysis of the most influential patents reveals that those related to physical storage demonstrate superior citation performance (Table 3). For instance, the 2002 patent from the University of California, "*lightweight cryogenic-compatible pressure vessels for vehicular fuel storage*" has been cited numerous times (over 60 times) by BMW, and to a lesser extent by Linde and GM. Another example is the 2003 patent from Air Products and Chemicals, "*self-contained mobile fueling station*" cited by several patents from Air Liquide, Honda.

Finally, the calculation of the density ratio in the network citation between applicants clearly demonstrates greater flow of knowledge and, above all, greater technological proximity between players in physical technology than in chemical and adsorption technologies (indicator 7, Table 4 and Fig. 8).

For the field of adsorption technology, it can be seen that there are only three linked applicants in the top: Toyota, Honda and Shanghai Huapeng Explosion-proof Technology Co. The situation is even more

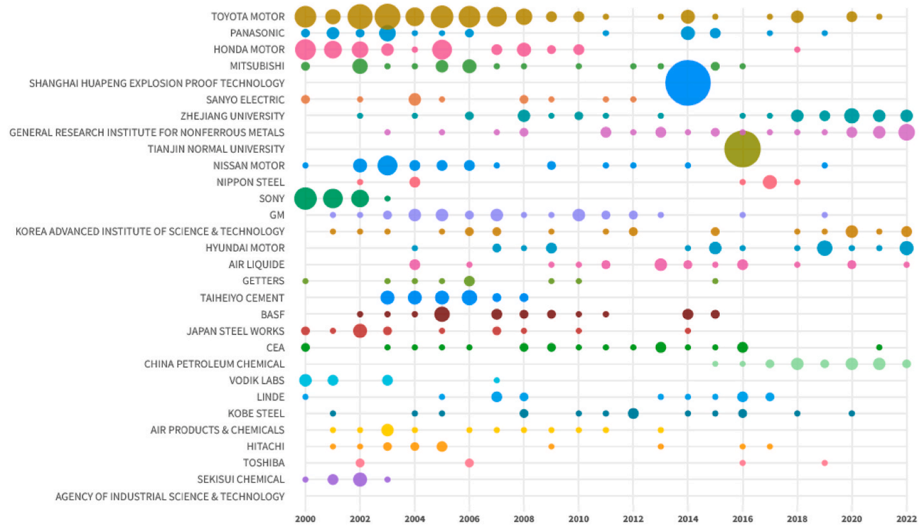

Fig. 5. Temporal evolution of patent application for top 30 applicants in absorption storage technology (Unit: Number of patent family by priority year).

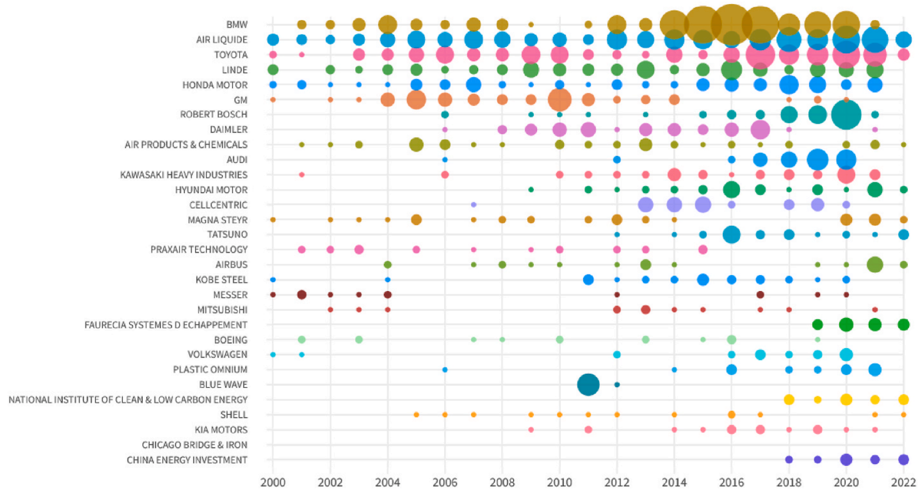

Fig. 6. Temporal evolution of patent application for top 30 applicants in physical storage technology (Unit: Number of patent family by priority year).

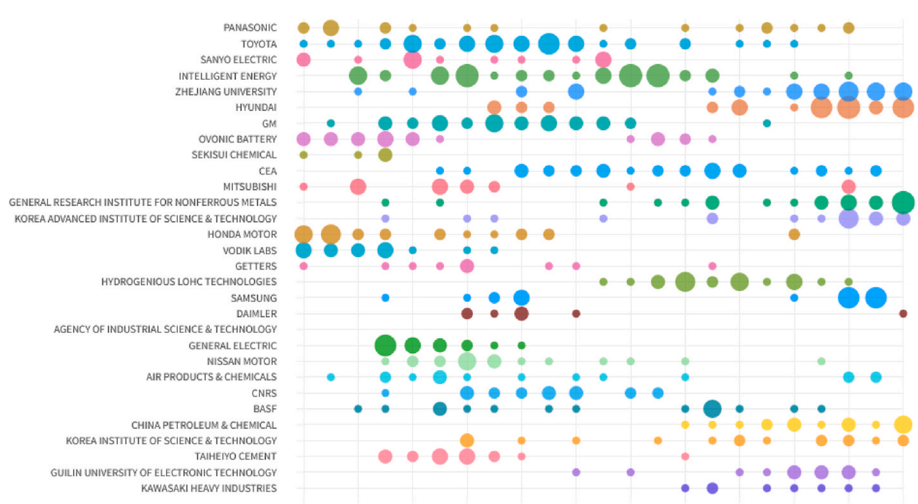

Fig. 7. Temporal evolution of patent application for top 30 applicants in chemical storage technology (Unit: Number of patent family by priority year).

Table 2
Indicators of persistence by technologies.

	Adsorption	Physical	Chemical
% of patents alive (average for the top 30 applicants)	29 %	65 %	40 %
Continuity of patent application activities of the main applicants (at least 10 consecutive years over the past 20 years)	2/30 applicants	9/30 applicants	4/20 applicants
Name of the applicants continuously active	Toyota, General Research Institute for nonferrous metals	BMW, Air Liquid, Toyota, Linde, Honda Motor, GM, Daimler, Kawasaki Heavy, Kobe Steel	Toyota, Intelligent Energy, GM, Hydrogeneous Lohc Technology

Table 3
The 5 most cited patents (Unit: Number of forward citations received by other patents in the technological field and average by year).

Rank	Patent number	Applicant	Number citation received	Average citation by year
Adsorption				
1	US6015041	Westinghouse Savannah River	65	2,5
2	US5458784	Catalytic material	54	2,0
3	US20020096048	Air Product Chemical	45	2,1
4	US20040016769	Liminia Fuel Cell Techno	40	2,0
5	CA2605695	Intelligence Energy	38	2,4
Physical				
1	US6708502	University of California	95	4,8
2	US20040163731	Air product Chemical	88	4,6
3	US20050178463	Gas Technology Institute	50	2,8
4	US20110259469	Honda	50	4,2
5	MY124701	Johns Hopkins University	49	2,1
Chemical				
1	US6015041	Westinghouse Savannah River	67	2,6
2	US20040016769	Liminia Fuel Cell Techno	59	3,0
3	DE19526434	SGK	58	2,1
4	US20010051130	Hawai University	42	1,8
5	CA2605695	BIC	41	2,6

Table 4
Density ratio of citation network between main applicants (Top 30).

	Adsorption	Physical	Chemical
Number linked applicants	3/30	25/30	2/30
Density ratio	0.1	0.8	0.07

restricted in the case of chemical technology, where the only significant citation link is between the patents of two specialists: Ovonics Battery and Vodiks Labs.

On the contrary, for physical hydrogen storage technology the network includes 25 applicants from the top 30. The applicants seem to exhibit notable technological similarities. To illustrate, the top applicant, BMW, cites numerous other applicants at a high level, particularly other carmakers in the field: Toyota (49 BMW patents cite the Japanese carmaker), Daimler (45) and GM (42). The most significant citation flow was identified between the two Japanese carmakers, Toyota and Honda. A total of 54 Honda patents (equivalent to 56 % of the number of patents held by Honda in the field) were found to cite at least one patent belonging to Toyota. In addition, 46 Toyota patents were identified as referring to Honda patents. Similarly, the gas and chemicals industries cite each other at a significant level. For example, Air Product & Chemicals is the player most cited by Air Liquide, and also refers to inventions by Linde, Praxair Technology and Messer. More generally, the 2 sets of manufacturers (from the automotive and chemical industries) have strong links in terms of citations. For example, Air Liquide, which is one of the most influential applicants, cited by almost half of the main top 30 applicants, has filed patents to which all the main car manufacturers refer, with the exception of Hyundai and Volkswagen.

4.4. *Step 4: overall evaluation of the production knowledge function*

In conclusion, the three technological areas under consideration exhibit distinct profiles in terms of knowledge production. While the physical route has fewer patent filings, it stands out for its highly structured approach to developing new knowledge. This is evidenced by stronger performance in terms of commitment, persistence, and coherence. For physical technology, the sustained efforts of multiple actors who have built substantial and enduring patent portfolios, coupled with the presence of high-impact patents, have contributed to the establishment of a robust knowledge base dominated by leading industrial players (notably hydrogen users and producers).

In contrast, investment in new knowledge creation for chemical and adsorption solutions appears to be more limited. The chemical pathway seems to be pursued by a small group of specialized actors who are firmly convinced of its potential. However, no strong mutual influence among these actors can be observed. Lastly, the situation for adsorption technology appears more precarious, despite significant interest reflected in high patent filings number. Our indicators point to a lack of consistency in the efforts of the stakeholders and a weakness in the process of building a cohesive and consensual knowledge base.

5. Discussion and conclusion

This article introduces a refined methodology for accurately characterizing the knowledge production function within the TIS framework, leveraging patent data as a key information source. The three proposed criteria—commitment, persistence, and coherence—alongside seven distinct indicators, provide a holistic approach to analysing this dynamic. This methodology integrates various perspectives on the technology under study, encompassing the quantity and continuity of recent and ongoing activities, the diversity of participating actors, the consolidation of technological consensus, and the identification of key actors who are particularly active and advocate strongly for the technology.

The insights gained from this methodology significantly enhance our understanding of the knowledge production function. For instance, relying solely on the number of patents filed to evaluate knowledge production in hydrogen storage could lead observers to conclude that the field is dynamic and progressing well, simply based on the volume of patented inventions. Such a conclusion would likely result in an optimistic outlook, as demonstrated by recent reports from the European Patent Office [46] and Bakker's 2010 study [47], both of which highlighted positive developments in hydrogen technology. Analysing the situation through the TIS framework might also suggest that the knowledge development function is effective, potentially leading to the conclusion that no further incentives are needed to encourage innovation, such as additional funding for demonstrators or research projects.

However, the proposed methodology reveals a more nuanced reality. While agents are exploring the various technological solutions quite well, with the exception of physical technologies, their efforts are rather disparate when it comes to tackling the main barriers blocking the

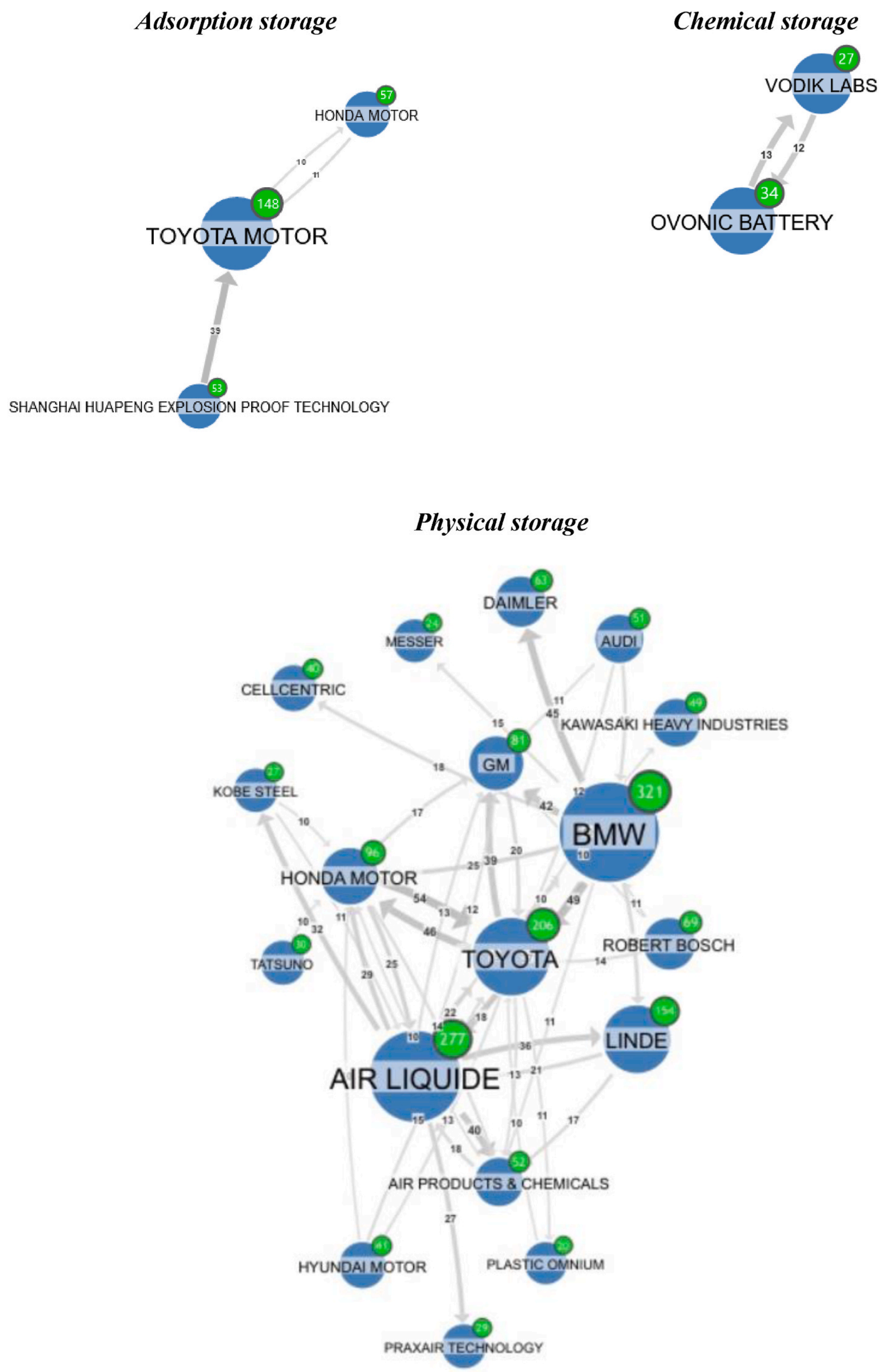

Fig. 8. Citation network between the main applicants
Unit: number on name applicant: number of patent application/number on link: number of citing patents.

development of concrete applications. The prospect of achieving this transition remains distant as long as the challenges of storing hydrogen on a large scale, safely, and affordably persist.

In conclusion, the methodological proposal presented in this article enables a more refined analysis of the knowledge production function within the TIS framework. This approach complements existing empirical tools by addressing some limitations of patent databases while preserving their strengths, such as global coverage and the ability to trace historical trajectories and identify key actors. However, while patent data can offer valuable insights into the functioning of a TIS, they are not sufficient on their own for comprehensive empirical studies. Additional methodologies, such as expert interviews and analyses of grey or academic literature, as well as other databases (scientific, financial, etc.), are essential. This methodology should therefore be viewed as a complementary tool for empirical analysis.

Moreover, the proposals in this article merit further exploration and refinement. Future research should assess the applicability of this methodology to other cases, which may reveal opportunities to enhance the selected indicators. A historical analysis, rather than the in vivo approach used here, could provide deeper insights, as demonstrated by previous studies on the development of technologies like pacemakers [48]. Additionally, comparing the three criteria and seven indicators proposed in this study with other indicator sets developed for predicting technological success could offer further advancements in understanding and application [49].

CRediT authorship contribution statement

Marina Flamand: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Vincent Frigant:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Stéphane Miollan:** Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: FLAMAND reports financial support was provided by Stellantis NV. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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None.

Appendix: Patent query details

PHYSICAL

(Y02E-060/32)/IPC/CPC AND (F17C-2223/0153 OR F17C-2223/0161 OR F17C-2223/0169 OR F17C-2223/013 OR F17C-2225/0153 OR F17C-2225/0161 OR F17C-2225/0169 OR F17C-2225/013 F17C-2225/0123))/IPC/CPC.

CHEMICAL

(Y02E-060/32)/IPC/CPC AND [(Y02E-060/32) AND (C01B6+ OR Y02E-060/327 OR C01B-003/0026 OR C01B-003/0031 OR C01B-003/0036 OR C01B-003/0042 OR C01B-003/0047 OR C01B-003/0052 OR C01B-003/0057 OR C01B-003/0063 OR C01B-003/0068 OR C01B-003/0073 OR C01B-003/0078 OR C01B-003/0084))/IPC/CPC OR (METAL HYDRIDE+)/TI/AB/CLMS/OBJ/ADB/ICLM.

OR (C01B6+ OR Y02E-060/327 OR C01B-003/0026 OR C01B-003/0031 OR C01B-003/0036 OR C01B-003/0042 OR C01B-003/0047 OR C01B-003/0052 OR C01B-003/0057 OR C01B-003/0063 OR C01B-003/0068 OR C01B-003/0073 OR C01B-003/0078 OR C01B-003/0084)/IPC/CPC OR (METAL HYDRIDE+)/TI/AB/CLMS/OBJ/ADB/ICLM OR (Y02E-060/328 OR C01B-003/025 OR C01B-003/04 OR C01B-003/042 OR C01B-003/045 OR C01B-003/047)/IPC/CPC OR (CHEMICAL HYDRID+) OR (HYDROGEN 3D CARRIER+) OR (LIQUID 3D CARRIER+) OR "LOHC" OR "LIQUID ORGANIC HYDROGEN")/TI/AB/CLMS/OBJ/ADB/ICLM OR (C01C-001+ OR H01M-008/222 OR C01B-003/047 OR C01B-003/025))/IPC/CPC OR ((NH3 OR AMMONIA)/TI/AB/OBJ/ADB/ICLM OR (C07C-031/04 OR C07C-031/08 OR H01M-008/1011 OR H01M-008/1013))/IPC/CPC OR (METHANOL OR ETHANOL OR BIOETHANOL)/TI/AB/CLMS/OBJ/ADB/ICLM]

ADSORPTION

(Y02E-060/32)/IPC/CPC AND (ADSORPTION OR (METAL ORGANIC FRAMEWORKS) OR (METAL ORGANIC FRAMEWORK) 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))/TI/AB/CLMS/OBJ/ADB/ICLM.

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