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Hydrogen Storage in Porous Rocks: A Bibliometric Analysis of Research Trends

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Abstract: Currently, there is an increasing number of research studies on underground storage of hydrogen in porous rocks (aquifers and depleted hydrocarbon fields). An important aspect of this process is the efficiency of hydrogen storage, which is defined as the correct operation of a storage facility (the ability to inject and withdraw an appropriate quantity of gas) and the safety of storage, which is influenced by numerous factors, including geological factors. With an increasing number of publications, gathering knowledge and keeping track of scientific progress is becoming increasingly complex. In addition to the technical interdependence of the parameters analysed, there are also interrelationships between scientific publications addressing issues related to underground hydrogen storage in porous rocks. The aim of this paper is to analyse the literature on hydrogen storage efficiency in porous rocks and, on the basis of the analysis, to identify the most important research trends and issues relevant to their implementation. This article presents an analysis of publications indexed in the SCOPUS database. The analysis included publications that contained expressions related to the relevant search phrases in their title, abstract or keywords. The dynamics of changes in the interest of researchers on the problem of hydrogen storage in porous rocks and the distribution of studies by geographical location (countries) are presented. Based on an analysis of the number of citations, the most influential publications were identified. Using the VOSviewer version 1.6.19 software, clusters reflecting research sub-areas were identified based on co-occurrence analysis, such as geological and reservoir aspects, reservoir engineering aspects, hydrogeological aspects and petrophysical aspects. Bibliometric methods have great potential for performing quantitative confirmation of subjectively delineated research fields and/or examining unexplored areas. The literature on underground hydrogen storage in porous rocks has been growing rapidly since at least 2018, with researchers conducting their studies in four major research streams: geological and reservoir aspects, reservoir engineering aspects, hydrogeological aspects and petrophysical aspects.

Keywords: underground hydrogen storage; porous rock; bibliometric analysis; research trends; SCOPUS

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1. Introduction

The implementation of a hydrogen economy is a necessary element for the development of a low-carbon economy. The use of hydrogen as an energy carrier and a raw material on a large scale requires the creation of an entire hydrogen economy value chain [1–6]. Large amounts of hydrogen produced in the future, especially from renewable sources, will require temporary storage. Hydrogen can be stored above ground in tanks and as a mixture with natural gas in natural gas grids (Power-to-Gas; P2G) [7–9]. Hydrogen storage methods can be divided into two basic categories—physical methods (H_2 compression, liquefaction and cryo-compression) and chemical (material) methods. [10,11]. In these methods, hydrogen is stored in various high-pressure and cryogenic vessels made of different types of materials that should not interact with hydrogen or cause other reactions (stainless steel, aluminium alloys and copper) [11,12]. Chemical methods are based on physical and chemical sorption processes. In these methods, hydrogen can be stored in vessels made of metal hydrides, magnesium-based materials, complex hydride systems, carbonaceous materials and metal–organic frameworks [4].

Both tanks and gas networks allow the storage of small amounts of energy (in the form of hydrogen) on the order of MWh for hours or days. Energy storage on the order of GWh/TWh over a period of more than a month requires sites with much larger storage capacities. Among the different hydrogen storage options, underground storage in geological structures is most suitable to store large amounts of hydrogen. Salt caverns, depleted gas reservoirs and aquifers are considered as potential sites for underground hydrogen storage (UHS) [4,13–18]. Geological structures in deep aquifers and depleted oil and gas reservoirs occur naturally. Leached caverns in rock salt are formed due to human activities. To date, experience with underground hydrogen storage on an industrial scale is limited to salt caverns. Hydrogen storage in porous media is so far in the research and testing phase. The first test storage sites have been commissioned in depleted gas fields in Austria and Argentina [18,19].

Hydrogen storage in geological structures in porous rocks has numerous advantages. In the case of aquifers, the advantages include a wide distribution and large capacity, as well as a high storage efficiency. In the case of depleted natural gas reservoirs, the recognised underground geology, the tightness of the storage formation, the residual gas and the existing infrastructure of these reservoirs are advantageous [20]. Hydrogen storage in porous rocks also has disadvantages. Recognising the geology, conducting extensive research and building infrastructure are necessary for constructing an H_2 storage facility in an aquifer. The integrity of structures in aquifers is not proven. The operating efficiency of H_2 storage facilities located in depleted natural gas reservoirs is lower, and infrastructure that can lead to hydrogen leakage is also present [21].

The efficiency of the hydrogen storage process in porous rocks, defined as the correct operation of a storage site (ability to inject and withdraw adequate amounts of gas) and the safety of storage, is influenced by geological factors. The porosity and permeability of the storage formation play the most significant roles in controlling the injection and withdrawal of hydrogen. The performance of underground storage is also influenced by geochemical/microbial reactions and geomechanical interactions. An underground storage site's safety is mainly determined by the integrity of the overburden rocks. Reservoir pressure, capillary pressure, wettability and phase tension all have an effect on the potential loss of tightness of overburden rocks.

The storage of hydrogen in porous rocks takes place in sedimentary basin zones that have a defined reservoir and sealing rock system. Deep aquifers and depleted hydrocarbon reservoirs occur in porous rocks. Hydrogen can be stored in voids (between mineral grains or fractures) that are present in various types of porous sedimentary rocks. A storage formation's porosity affects the amount of gas that can be stored. It is necessary for rocks where hydrogen storage is located to have a high gas transmissivity (high permeability) [22]. Permeability determines the rate at which hydrogen is injected into and withdrawn from an underground storage site. Gas storage facilities can be located in deep aquifers containing highly saline, non-potable water. Hydrogen storage facilities are created in closed geological structures. In aquifers, these are elevated anticlines. Hydrocarbon deposits, on the other hand, are geological traps in which oil and gas deposits have accumulated.

A storage formation must be covered with poorly permeable rocks (caprock). Rocks with the best sealing properties are salts, anhydrites and claystones. The seal should provide protection against hydrogen leaking from the storage formation towards the surface. The challenges of underground hydrogen storage arise from the amount of gas stored and the properties of hydrogen, a gas with the smallest molecule among gases, as well as high mobility and diffusivity [17]. A rock formation intended for hydrogen storage, as well as the overburden rocks, should not be tectonically involved (no fractures or faults), which may provide migration paths for hydrogen gas towards the surface [15,23,24]. A loss of caprock containment can also occur as a result of physicochemical reactions of hydrogen with brine, oil or reservoir rocks and microbial reactions [25–28]. Hydrogen can also leak through a caprock as a result of molecular diffusion. Due to hydrogen's very small molecular size and high mobility properties, its diffusion through sealing rocks is possible [21,29]. The integrity of a caprock is also dependent on its capillary sealing efficiency. Capillary sealing efficiency depends on the properties of overburden rocks, including their wettability, interfacial tension, threshold pore radius and fluid densities [29–31].

Geological structures (aquifers and hydrocarbon deposits) in porous rocks have various characteristics. Aquifers are characterised by their potentially large hydrogen storage capacities [32]. Prior to hydrogen injection, and due to poor geological recognition, numerous expensive research investigations are required [29,33]. Depleted natural gas reservoirs have a well-recognised geology and proven tightness. The residual gas remaining in a depleted reservoir can be used as cushion gas [29,34,35]. Potential problems associated with hydrogen storage in gas reservoirs may arise from geochemical/biochemical reactions occurring in the storage formation and overburden rocks. One of these problems is the potential loss of containment and hydrogen leakage [18,29].

Cyclic hydrogen injection can cause several phenomena that affect the integrity of an underground storage site [18,36]. The introduction of hydrogen into a geological structure will lead to an increase in pressure and, thus, to changes in the stress pattern in and around the storage formation (see [37–39]). Cyclic stress fluctuations in the reservoir and fault formation can cause compaction of the reservoir horizon, leading to reduced porosity and reduced reservoir fluid flow, subsidence, reactivation of faults or excitation of microseismicity [37,40–42]. The magnitude of the various phenomena that occur in an underground storage site will vary over time and, therefore, affect the integrity of the storage site [43,44].

The operation of hydrogen storage in an aquifer is also influenced by the reservoir pressure. Aquifers in sedimentary basins can be open or closed (structural traps). In an open aquifer, the injected hydrogen can diffuse laterally. In a closed aquifer, H_2 is held in a confined space with buoyancy forces under impermeable rocks [45]. In a closed structural trap, hydrogen injection results in an increase in pressure (fracturing and capillary). Therefore, the pressure value must be kept below the maximum pressure (fracturing pressure) to maintain the mechanical integrity of the storage site [46,47].

The injection of large volumes of gas can cause damage to the integrity of a storage site and caprock [48]. Deformation in the storage formation, the sealing caprock and faults may occur due to swelling of clay minerals [49,50]. This affects the long-term stability and safety of an underground storage site [28,51]. Also, geochemical reactions (dissolution/precipitation of minerals and sorption/desorption of clay minerals) may contribute to the formation of fissures and fractures [52], and the superposition of their effects, particularly within faults, affects their stability.

During underground hydrogen storage, geochemical interactions may occur that involve the stored hydrogen, cushion gas, reservoir fluids and minerals [27,53]. These reactions can convert hydrogen to other gases (methane and hydrogen sulphide), which results in a loss of stored hydrogen. Geochemical processes can reduce the purity of hydrogen [54,55]. Geochemical reactions can also change reservoir porosity and permeability. As a result of the modification of petrophysical parameters, the geomechanical properties of a storage formation may change. The integrity of a caprock can be reduced by changes in geomechanical properties [18,56]. The most important geochemical interactions are those that occur in the presence of water and mineral dissolution/precipitation reactions [27,56]. One important factor to consider during UHS is microbially induced reactions, including methanogenesis, acetogenesis and sulphate reduction [57–61]. It is expected that in the presence of high-salinity brines, the action of reducing bacteria is slower [62]. Underground hydrogen storage can benefit from the experience of the oil industry to better understand it, e.g., the two-phase flow of viscoelastic polymer and oil [63] or the effect of the interface structure and behaviour on fluid flow characteristics and phase interactions for advancement in the field [64].

Underground hydrogen storage is a technology that has been developed since the 1970s. However, the UHS experience has primarily been focused on hydrogen storage in salt caverns. Options for underground hydrogen storage in porous rocks (aquifers and hydrocarbon reservoirs) are currently in the research stage. Significant challenges must be overcome before hydrogen storage in porous rocks can be introduced on a large scale. Hematpur et al. point out that specific issues that need to be considered for underground storage in porous rocks are the possibility of bacterial degradation, the mixing of hydrogen with pillow gas, the loss of hydrogen through capillary capture with water, and the effect of Ostwald maturation on reducing hysteresis [65].

A bibliometric analysis of scientific publications was performed to identify the most and least frequently presented research topics on hydrogen storage efficiency in aquifers and hydrocarbon reservoirs. The subject of the analysis included scientific publications indexed in the SCOPUS database. An analysis of the number of articles that were published in each year allowed us to characterise the dynamics of changes in researchers' interest in issues related to hydrogen storage in porous rocks. Citation analysis was used to identify the most impactful publications. Co-occurrence analysis allowed the separation of sub-areas in the area of hydrogen storage efficiency in aquifers and hydrocarbon reservoirs. The bibliographic analysis aimed at highlighting the most recent literature and revealing the underlying research trends. On this basis, major research topics were identified and the level of research progress was examined. This has made it possible to identify research topics requiring more research before starting industrial hydrogen storage projects in porous rocks.

2. Materials and Methods

The research method used to evaluate publications in the area of underground hydrogen storage in porous rocks was bibliometric analysis. Bibliometric analysis tracks publications in a research area through assessments of the co-occurrence of words and their co-classification, co-authorship of research papers and interpretation of citations. Bibliometrics is a quantitative analysis of publications aimed at performing information functions concerning the development of a selected research area [66]. Bibliometrics can be used for the following:

- Anticipation of future research trends in a given area;
- Identification of areas in need of research (search for knowledge gaps);
- Identification of links between research areas;
- Identification of areas of relatively high research saturation;
- Trend analysis of a research area.

The bibliographic/abstract interdisciplinary database SCOPUS was utilised as the data source for this study (research material). Publications on the effectiveness of the hydrogen storage process in porous rocks were analysed. A search was performed for scientific publications that contained in their title, abstract or keywords the following phrases presented in Figure 1.

Research techniques including trend analysis, citation analysis and co-word analysis were used [67].

- Trend analysis is an assessment of the dynamics of changes in the number of publications over the analysed period.
- Citation analysis is used to assess and compare publications on the basis of frequency of citations. A citation index indicates the level of interest of other authors on a particular publication.
- Co-word analysis is based on counting the frequency of occurrence of word pairs in the analysed text. Such an analysis makes it possible to identify the regularity of the co-occurrence of words.
- Co-occurrence of words can signal the existence of sub-areas of research or identify the directions of development of a research area. The analysis can be carried out at the

level of different text elements, including titles, abstracts, keywords, the actual text of publications or on the basis of various combinations of these elements.

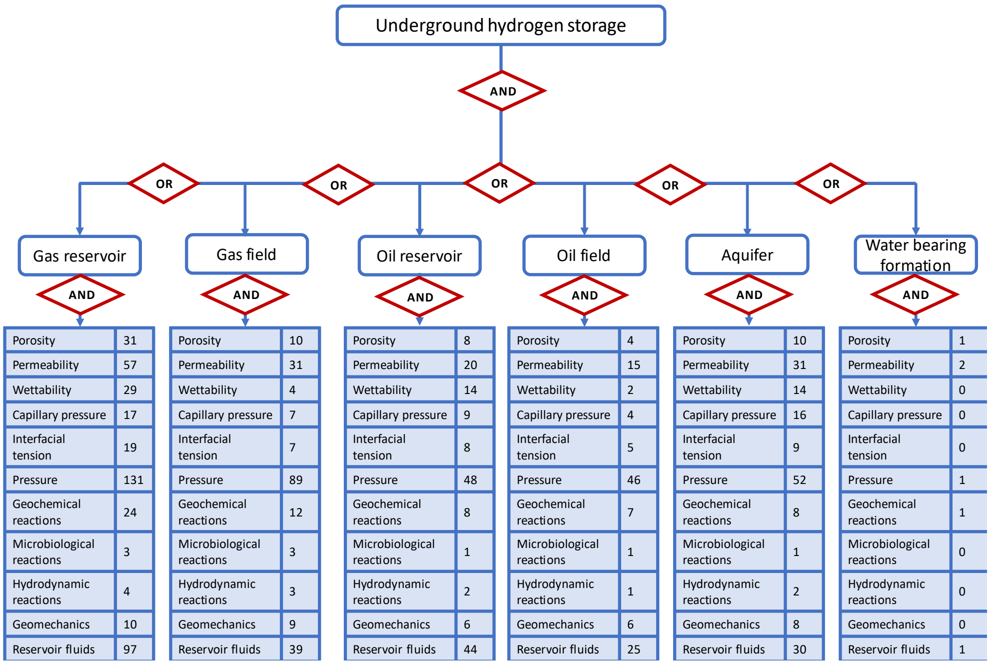

Figure 1. Scheme of SCOPUS search for publications on hydrogen storage efficiency in porous rocks (keywords and number of publication).

Co-word analysis was carried out using the specialised software VOSviewer version 1.6.19 —Visualising Scientific Landscapes by Nees Jan van Eck and Ludo Waltman [68]. The VOSviewer programme is a software tool for building and visualising bibliometric networks. These networks can, for example, include journals, researchers or individual publications and can be constructed based on citations, bibliographic linking, co-citations or co-authorship relationships. VOSviewer also offers a text mining function that can be used to construct and visualise co-occurrence networks of important terms from the scientific literature [69]. Identification of key research strands within the field was carried out via mapping using VOSviewer, which is able to group related elements through colour-coding them. VOSviewer allows the construction and review of bibliometric maps [70].

The scope of the research carried out included the following stages:

- Assessment of changes in the number of publications in the study area analysed over a specific time horizon in the Scopus database;
- Identification of publications of key relevance to the research area under analysis based on citations;
- Identification of research sub-areas in the bibliometric dataset based on an analysis of the most frequent phraseological compounds in the SCOPUS database using VOSviewer.

3. Results and Discussion

The total number of documents found in the SCOPUS database was 1023. The retrieved documents were verified (duplicate records and off-topic publications were removed). After removing duplicate records, 261 publications remained for the bibliometric analysis.

3.1. Trend Analysis

The first element of the bibliometric analysis was a time series analysis, reflecting the number of publications included in the SCOPUS database. The first publication on the issue of underground storage of hydrogen in porous media appeared in 1986 and was an article in the journal *International Journal of Hydrogen Energy* entitled "Technical and economic assessment of methods for the storage of large quantities of hydrogen" by Taylor J.B., Alderson J.E.A., Kalyanam K.M., Lyle A.B., and Phillips L.A [71].

The data presented in Figure 2 confirms the steadily growing interest in the issue of underground hydrogen storage, as reflected by the increasing number of publications. In the initial phase between 1985 and 2020, the number of publications did not exceed a dozen per year. From 2020 to the present, there has been a significant increase in interest on the research topic under consideration, as confirmed by the steep, almost vertical line of the graph.

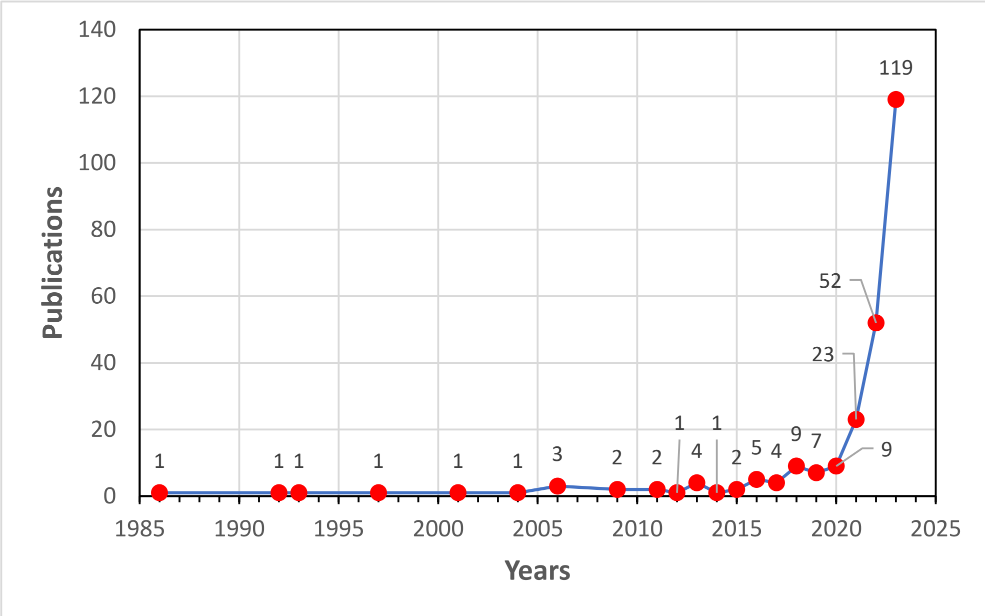

Figure 2. Number of publications (red dots) on underground hydrogen storage in porous media in the SCOPUS database.

The mechanism for aggregating data from records (bibliographic descriptions of articles) makes it possible to analyse the publication output geographically, including identifying the country of origin of authors with the largest number of publications on a given topic, the scientific centres of these authors, and the most frequently published and cited researchers. Most of the authors publishing in the field of underground hydrogen storage in porous media come from the United States (50), Australia (45) and China (39) (Table 1).

Table 1. Spatial distribution (by country) of authors publishing in the SCOPUS database.

Country	Documents	Citations
United States	50	617
Australia	45	934
China	39	496
Germany	34	1117
Saudi Arabia	29	385
United Kingdom	25	775
The Netherlands	19	539
Poland	19	316
France	18	742
Austria	12	96
Iran	11	375
Canada	10	338
Norway	10	167
Italy	9	31
United Arab Emirates	9	8
Malaysia	8	464
India	5	157

3.2. Citation Analysis

Articles on underground hydrogen storage in porous rocks that were published in the specified time interval (1985–2023) were accepted for this study; the 262 publications qualified for the review were written by a total of 928 authors, of which only 6 articles were single-author papers. The total number of citations for the articles analysed (261) was 5494. The average number of citations per paper was 21.05. The data presented in Figure 3 confirm the steadily growing interest in the topic of underground hydrogen storage, as reflected by the number of citations. In the initial phase between 1985 and 2017, the number of citations did not exceed 200 per year. From 2017 to the present, there has been a significant increase in interest in the research topic under consideration, as confirmed by the line of the graph. The data presented show a strong positive correlation between the number of publications and citations during the analysed period.

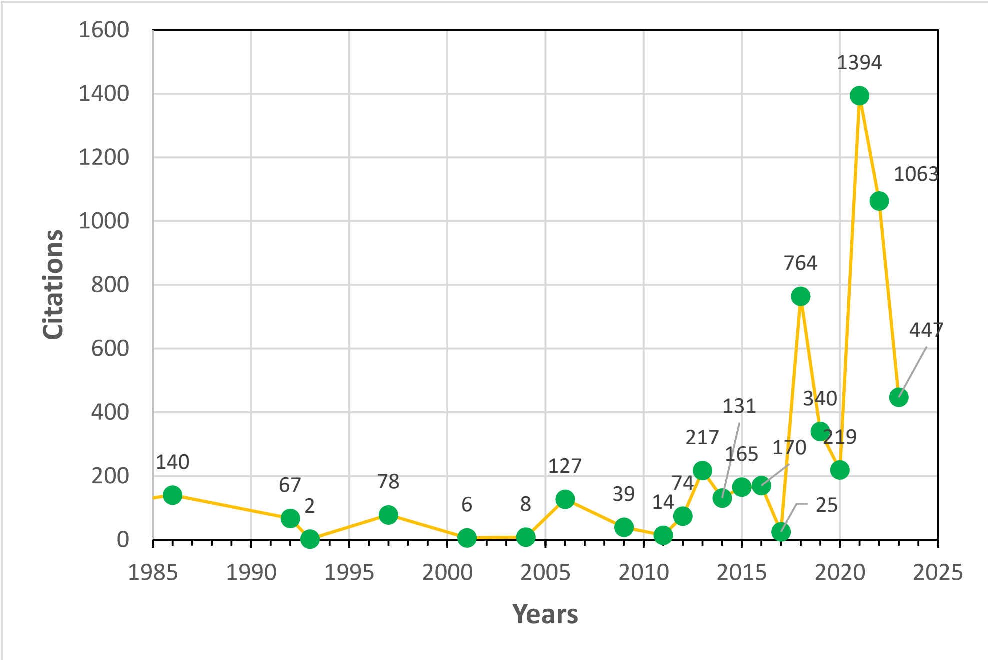

Figure 3. Number of citations of publications (green dots) on underground hydrogen storage in porous media in the SCOPUS database.

Table 2 shows the most influential articles (100 citations or more) ranked by the number of citations in the SCOPUS database among the sample of 261 articles on underground hydrogen storage in porous rocks. These rankings show papers that are considered the most groundbreaking in the field, journals that are deemed most suitable for publication, and authors whose work has attracted the most interest.

Table 2. Most influential articles on underground hydrogen storage in porous rocks.

Authors	Title	Year	Journal	Citations
Zivar, D., Kumar, S., Foroozesh, J.	"Underground hydrogen storage: A comprehensive review" [18]	2021	*International Journal of Hydrogen Energy*	340
Heinemann, N., Alcalde, J., Miocic, J. M., Hangx, Suzanne J. T., Kallmeyer, J., Ostertag-Henning, C., Hassanpouryouzband, A., Thaysen, E.M., Strobel, G.J., Schmidt-Hattenberger, C., Edlmann, K., Wilkinson, M. Bentham, M.S., Haszeldine, R. Carbonell, R., Rudloff, A.	"Enabling large-scale hydrogen storage in porous media-the scientific challenges" [72]	2021	*Energy and Environmental Science*	262

Table 2. *Cont.*

Authors	Title	Year	Journal	Citations
Matos, C.R., Carneiro, J.F., Silva, P.P.	"Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification" [73]	2019	*Journal of Energy Storage*	210
Taylor, J.B., Alderson, J.E.A., Kalyanam, K.M., Lyle, A.B., Phillips, L.A.	"Technical and economic assessment of methods for the storage of large quantities of hydrogen" [71]	1986	*International Journal of Hydrogen Energy*	140
Panfilov, M.	"Underground and pipeline hydrogen storage" [19]	2015	*Compendium of Hydrogen Energy: Hydrogen Storage, Distribution and Infrastructure: Volume 2*	132
Bai, M., Song, K., Sun, Y., He, M., Li, Y., Sun, J.	"An overview of hydrogen underground storage technology and prospects in China" [74]	2014	*Journal of Petroleum Science and Engineering*	131
Hemme, C., van Berk, W.	"Hydrogeochemical modelling to identify potential risks of underground hydrogen storage in depleted gas fields" [75]	2018	*Applied Sciences (Switzerland)*	115
Feldmann, F., Hagemann, B., Ganzer, L., Panfilov, M.	"Numerical simulation of hydrodynamic and gas mixing processes in underground hydrogen storages" [76]	2016	*Environmental Earth Sciences*	114
Flesch, S., Pudlo, D., Albrecht, D., Jacob, A., Enzmann, F.	"Hydrogen underground storage—Petrographic and petrophysical variations in reservoir sandstones from laboratory experiments under simulated reservoir conditions" [77]	2018	*International Journal of Hydrogen Energy*	111
Luboń, K., Tarkowski, R.	"Numerical simulation of hydrogen injection and withdrawal to and from a deep aquifer in NW Poland" [78]	2020	*International Journal of Hydrogen Energy*	100

The articles with the highest number of citations are review articles that highlight issues concerning hydrogen storage in porous rocks, including issues related to the efficiency of this process (Table 2) [15,18,19,71,73,74]. The remaining articles present results obtained from numerical simulations (hydrogeochemical and hydrodynamic models) and laboratory studies. The studies presented in these articles deal with the efficiency of underground hydrogen storage, such as H_2 injection/withdrawal [78], mixing processes that occur at a storage site [76], and risk issues related to hydrogen storage in natural gas reservoirs [75]. One publication presents the results of a study under different reservoir conditions on the feasibility of hydrogen underground storage in selected sand and siltstone formations [77].

3.3. Bibliographic Coupling Analysis

The scientometric literature that analyses publications qualitatively and quantitatively indicates that two documents are bibliographically coupled if they have at least one reference in common [79,80]. In this study, bibliographic coupling analysis was carried out for keywords included in the publications on hydrogen storage efficiency in porous rocks indexed in the SCOPUS database. The VOSviewer version 1.6.19 software was used for this purpose. The co-occurrence analysis of words allows the grouping of publications into clusters reflecting research sub-areas.

The bibliographic coupling network is shown in Figure 3. The nodes symbolise the keywords included in the publications. The lines represent common references between any two keywords (i.e., bibliographic couplings). The thickness of the lines connecting each pair of words depends on the number of common references. The frequency of occurrence of a word is reflected by the size of the circles placed in the nodes, while the distance between the circles (representing word pairs) depends on the frequency of their co-occurrence. Identification of key research strands within the field was carried out through the means of keyword mapping using VOSviewer. To ensure the aesthetics and usability of the schema, the "Fractionalisation" normalisation method was adopted. Four research clusters were highlighted using the VOS algorithm. These are represented using different colours (see Figure 4). Articles belonging to the same clusters are visualised using a specific colour. The highlighted clusters are related to the following issues on the effectiveness of hydrogen storage in aquifers and hydrocarbon reservoirs:

- Geological and reservoir aspects—Cluster 1 (10 items): gas storage, geology, hydrocarbon reservoir, hydrogen, hydrogen, hydrogen storage, oil field equipment, porous medium, rock, underground gas storage and underground storage.
- Reservoir engineering aspects—Cluster 2 (6 items): cushion gas, depleted gas reservoir, gases, numerical models, petroleum reservoir engineering and petroleum reservoirs.
- Hydrogeological aspects—Cluster 3 (4 items): aquifers, dissolution, hydrogeology and underground hydrogen storage.
- Petrophysical aspects—Cluster 4 (4 items): caprock, contact angle, sandstone and wetting.

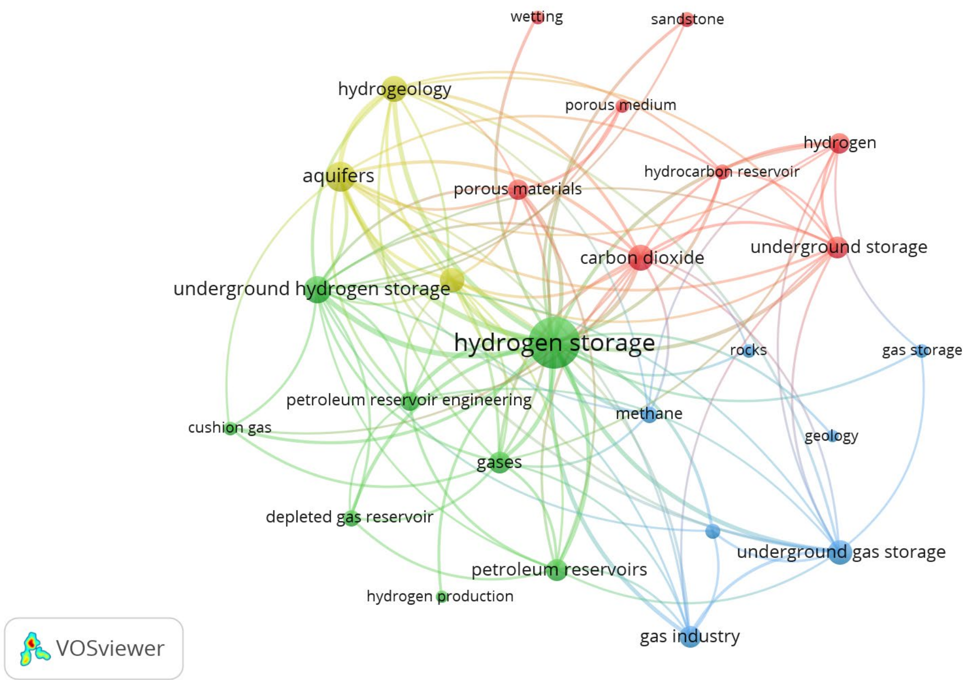

Figure 4. Visualisation map of keywords related to hydrogen storage in porous rocks.

The highest frequency of occurrence in the analysed publications has the keyword "hydrogen storage" (189). The next most frequent keywords are "aquifer" (78) and "underground hydrogen storage" (70). Among the analysed keywords, the five keywords that have a frequency of occurrence below 20 times are dissolution, contact angle, caprock, numerical models and hysteresis. The lower frequency of these keywords may indicate a small number of publications concerning studies on overburden rocks, geochemical processes (including dissolution), caprock phenomena and modelling of the UHS process. The listed topics included in Clusters 2 and 4 are poorly recognised and require further research.

3.4. Key Research Trends—Current Status and Prospects

Selecting a suitable storage site is crucial for the success of hydrogen storage in porous rocks. Thus far, no uniform criteria have been developed for the selection of structures for underground hydrogen storage, although attempts of this kind have been made [18,73,81]. Hydrocarbon reservoirs have been identified as being able to provide secure storage. The geology of aquifers is generally less well recognised. The tightness of structures in aquifers requires confirmation through numerous studies [17].

Important aspects related to underground hydrogen storage include the geochemical, geomechanical and microbial interactions between hydrogen and rock formations and reservoir fluids (such as water, natural gas and oil). These reactions can have both positive and negative affects on reservoirs and overburden rocks (mineralogical and petrophysical changes), as well as the quantity and quality of stored hydrogen [82]. They can also cause a reduction in reservoir capacity over time [83]. Sandstone rocks rich in quartz are suggested to be preferable for hydrogen storage. Calcite is a mineral that readily reacts with hydrogen, and, therefore, its presence in reservoir rocks is undesirable [27,54,77]. The geochemical interactions of hydrogen with other rocks require further study. Microbial activity is higher in aquifers than in gas reservoirs. The potential undesirable effects of microbial interactions include the formation of gases (H_2S and CH_4) and acids, corrosion, clogging and dissolution of reservoir rocks [25]. Cyclic injection and withdrawal of hydrogen into and out of rocks leads to numerous geomechanical phenomena that affect the integrity of underground storage [18,72]. Reservoir compaction can lead to overburden deflection and potential migration pathways for hydrogen [18,72,84]. The presence of clay minerals may result in geomechanical deformation due to dissolution and precipitation of minerals, as well as sorption and desorption [43]. To understand geochemical, microbiological and geomechanical interactions at specific storage sites, it is necessary to conduct interdisciplinary studies that involve microbiologists, geochemists, petrophysicists and geomechanists.

The use of cushion gas is crucial for underground hydrogen storage operation. Other gases, such as nitrogen or carbon dioxide, can be used as a cushion gas instead of hydrogen. To optimise the hydrogen storage process, the amount of cushion gas used in different structures needs to be analysed. The mixing processes of the cushion gas and the injected gas, as well as the interactions between the gas and liquid phases in the storage, are poorly studied [34,35,85].

The effectiveness of capillary hydrogen storage sealing depends on the properties of the overburden rocks at a storage site, including their wettability, interfacial tension, threshold pore radius and fluid densities [29–31]. Numerous studies have been carried out in recent years to examine the wettability of hydrogen, rocks and brine, and the importance of capillary sealing for geological hydrogen storage [86–88].

3.5. Bibliometric Analysis—Limitations and Perspectives

Low-quality analyses may result from weaknesses in bibliographic descriptions, which include article titles, keywords and abstracts. The content of a paper may not be accurately represented by its title. It is possible for the article to lack the content that was 'declared' in the title due to exaggerated formulation. A common occurrence is the incorrect selection of keywords that do not accurately reflect the research problem being addressed. Co-occurrence analysis of keywords is challenging due to the semantics of scientific terms, including their dependence on context, ambiguity and inadequacy for certain concepts. Article abstracts fail to include the necessary elements like the scientific objective, research methods, results obtained, and research findings. Typically, the abstract is the first section of the paper that is read or analysed. This is a crucial element of a publication, but it is often neglected.

Bibliographic studies are increasingly using IT tools. As a result of this computerization, there is now a great variety of data processing algorithms on which publication clustering operations are carried out. As interest in a specific scientific field, such as underground hydrogen storage, increases, the number of publications related to it increases significantly. Interdisciplinary publications frequently appear. The enormous number of publications, papers, and scientific dissertations means that increasingly sophisticated research methods are required for bibliographic analysis. These methods use increasingly complex research algorithms, analogous to those currently used in broad-based Artificial Intelligence, AI.

The literature analysis of hydrogen storage in porous rocks presented in this paper can be used as a basis for further in-depth analyses. A closer examination of citations, such as co-citations, clustering, or analysis of bibliographic links, could allow for identification of research trends in the topic being analysed and the relationships between them.

Separating subsets (clusters) of scientific publications is a common method used in this paper to identify trends in scientific disciplines. Research topics within the theme of hydrogen storage in porous rocks or problem areas are represented by clusters. These topics have the potential to develop at their own pace and direction.

In further work to identify research trends and the evolution, post-emergence, and disappearance of problem areas on the topic of hydrogen storage in porous rocks, the method of co-occurrence of terms taken from publication titles could be used [89].

Analysis would allow for distinguishing the most important research themes that dominate at different times and tracing how their role has changed for the topic of hydrogen storage in porous rocks as a whole.

An analysis of current research trends and recent intellectual trends on the topic of hydrogen storage in porous rocks can be performed using the method of co-occurrence of terms (hotspots). This analysis uses not only the author's keywords, but also the so-called 'extra' keywords (KeyWords Plus) available in the WoS database. These are the titles of publications in the articles bibliographies. The KeyWords Plus words are added using a special algorithm [90]. According to some researchers, KeyWords Plus words are oriented more than the author's words toward the novelty and innovation of the research directions of the research undertaken and referred to in the publications, rather than their traditional and more deeply rooted form in science [91,92].

4. Conclusions

In the near future, with the development of a hydrogen economy, options for storing large quantities of hydrogen will be sought. For these purposes, naturally occurring geological structures in deep aquifers and depleted oil and gas fields seem to be most suitable.

The results reveal that the literature on underground hydrogen storage in porous rocks has been growing rapidly since at least 2018, with researchers conducting their studies in four major research streams: geological and reservoir aspects, reservoir engineering aspects, hydrogeological aspects and petrophysical aspects.

The main obtained results can be summarized as follows:

- Currently, hydrogen storage in aquifers is in the research phase.
- Most of the studies reviewed in this paper recognise that the most important issues related to this topic are the efficiency of the hydrogen storage process (injection, hydrogen withdrawal and the safety of the process).
- Parameters such as porosity and permeability of the storage formation, geochemical and microbial reactions, geomechanical interactions, and the tightness of overburden rocks are related to these issues. These parameters, in turn, depend on many other factors, such as reservoir pressure, capillary pressure, wettability and phase tension.
- In addition to the technical interdependence of the parameters analysed, there are also interrelationships between scientific publications addressing the above-mentioned issues.
- Science mapping is becoming increasingly important due to the rapidly growing number of publications, and their fragmentation knowledge accumulation is becoming increasingly complex.
- Bibliometric methods have great potential in quantitatively confirming subjectively delineated research fields and/or examining unexplored areas.
- The results of the literature analysis on hydrogen storage in porous rocks presented in this paper may constitute the basis for further in-depth analyses. More detailed research on citations, e.g., co-citations, their clustering, or analysis of bibliographic connections, could allow for the identification of research trends for the analysed topic and the relationships between them.

- To identify research trends and their evolution, as well as the emergence and disappearance of problem areas in the field of hydrogen storage in porous rocks, it can be beneficial to use the method of co-occurrence of terms taken from publication titles (hotspots), and so-called additional words (KeyWords Plus).
- The use of advanced research methods for bibliographic analyses is necessary due to the large number of publishers, publications, and scientific disciplines. The research algorithms used by these methods are becoming more complex. Without their use, conducting in-depth bibliographic analyses is now impossible.
- The weakness of bibliographic descriptions, which may translate into low-quality analyses, is the poorly specified article titles, keywords, and article summaries. The authors of the publication can solve this problem by being more careful in preparing all components of the publication.

Keeping abreast of the latest scientific trends and identifying the most forward-looking, priority topics and research questions (hot topics) can allow researchers to keep up with the rapid, multifaceted development of science. Furthermore, they should rationally focus their research efforts. Monitoring research trends would facilitate their planning for future research collaborations.

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