Monitoring the developmental trend and competitive landscape of natural gas hydrate using patent analysis

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Research Article

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Posted Date: July 10th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3087553/v1

Monitoring the developmental trend and competitive landscape of natural gas hydrate using patent analysis

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Abstract: Natural gas hydrate (NGH) is an important alternative energy resource to achieve carbon neutral. The developmental trend and competitive landscape of NGH exploitation and production play a crucial role for policymakers in government, managers of enterprises, and science researchers. This paper proposes a new framework to carry out in-depth analysis of NGH by combining patentometrics, technologies evolution and correlation relationships to monitor developmental tends and competitive landscape using patent analysis. The results show that China, the US, and Japan hold a clear advantage using patents analysis. The current technological development in NGH field is more oriented towards extraction technologies, equipment, and processing systems. The co-opetition analysis among countries reveals that the largest international cooperation network is mainly in Europe and the United States, while national partnerships in Asia are mainly in China and Japan. The cooperation among institutions is still low and occurs mainly within universities in China, whereas both the US and Japan have cooperation between enterprises. The competitive landscapes of NGH-related key technologies among countries and institutions are also discussed. This study not only contributes to monitoring the developmental trend and competitive landscape in NGH but also provides policy recommendations for the government and enterprises on strategic management and collaborative innovation.

Keywords: patent analysis, developmental trend, competitive landscape, natural gas hydrate, ITGInsight

1 Introduction

As the energy crisis worsens, and the development and utilization of new energy sources is gaining widespread attention (Vedachalam *et al.,* 2015). Natural gas hydrate (NGH) is a crystalline solid formed by a mixture of methane and water under high pressure or low temperature. It is known as combustible ice, which is widely distributed on the marine sediments and terrestrial permafrost (Kvenvolden, 1988; Zhao *et al.,* 2022). NGH has become an important transitional energy source in the process of achieving carbon peaking and carbon neutrality in Europe, the United States of America (US), and China. (Wei *et al.,* 2021) because of its cleanliness, accessibility, wide distribution, ease of storage and security of supply. Currently, there are over 230 areas worldwide where NGH are to be explored and developed, and the global resource of NGH is approximately $2.1*10^{16}$ cubic metre, which is twice the total resources of existing fossil energy on land (coal, oil, and the standard NGH) (Kvenvolden, 1999; Musakaev, Khasanov and Borodin, 2018). NGH has become one of the most promising new energy resources and is considered to be an ideal alternative energy source for the 21st century (Collett and Dallimore, 1999; He *et al*., 2021; Makogon, Holditch and Makogon, 2007). It has attracted a growing number of companies and academics worldwide to conduct relevant research.

Many countries around the world are actively developing NGH industry including the US, Russia, Canada, Japan, Korea, China, and India. The US is at the forefront of NGH research in the world and is the most active in research into exploration and extraction techniques. In 1968, the US conducted its NGH investigation at the Black Sea Plateau (Chazallon *et al.,* 2021). Until the 21st century, research efforts on marine NGH in the US have focused on the Gulf of Mexico. In Japan, the exploration program for NGH in the Nankai Trough was made a priority in 1995, and large-scale exploration tests for NGH samples were conducted in the eastern part of the Nankai Trough from 1999 to 2000, but the expected high grade NGH deposits were not found (Oyama and Masutani, 2017; Tsuji *et al.,* 2004). China's NGH resources in the South China Sea are huge, about 80 billion tonnes of oil equivalent, which is equivalent to more than half of China's total onshore oil and gas resources (Gao, 2020; Kong *et al.,* 2018). On May 18, 2017, China announced the successful test mining of NGH, which was the world's first that achieve the continuous and steady flow of gas from NGH in marine area (Li *et al.,* 2018). However, NGH exploitation and production has fallen far short of public expectations, even though NGH has attracted a lot of attention from academics and countries. However, the current NGH technologies are not yet ready for large-scale industrial mining. At present, NGH is still at the early stage of commercialization, and the economics of extraction under existing technology and resources are low (Ye *et al.,* 2022). Hence there exists a considerable gap from research and development (R&D) to the mass production for NGH. Moreover, because of the importance of NGH as an alternative to existing energy sources, various countries are pressing ahead with R&D and strategic deployment of NGH-related technologies (Kong *et al.,* 2018). Therefore, it is crucial for researchers and engineers to understand the developmental trends for forecasting technology opportunities in NGH. Meanwhile, evaluating the competitive landscape of NGH technology is crucial for policymakers and managers to create an effective R&D strategy. Understanding the developmental trends of NGH is helpful for us to grasp the history of technological development, identify current research hotspots and indicate R&D directions (Wang, X. *et al.,* 2022). Technological competitive landscape analysis refers to the process of analyzing and determining external scientific and technical information that can have a significant impact on the organization's competitive position (Li *et al.,* 2022; Wang, X. *et al.,* 2022).

The existing literature on the developmental trends and the competitive landscape in NGH is still in its infancy, such as identifying research hotspots and frontiers by using bibliometrics analysis (Seo, Han and Sohn, 2015), statistical analysis (Wang, H. *et al.,* 2022), and systematic literature review on the NGH-related technologies (Komatsu *et al.,* 2013; Veluswamy *et al.,* 2018; Wei *et al.,* 2022; White *et al.,* 2020; Wu *et al.,* 2021). Despite this, there is a lack of patent-based reviews and bibliometrics on the various technical themes of marine NGH. Because of the high complexity and uncertainty nature of NGH exploitation and production, it is difficult to evaluate the developmental trends and the competitive landscape with bibliometrics or literature review. To address this, it is our belief that patents, which comprises about 80% of the world's technology knowledge, can be used as an important pillar for forecasting technology opportunities and making strategic decisions by government and firms. Because patents data contains key research findings, it is ideal as a strong indicator of technological innovation and progress. The study of patents allows us to understand competitors and competing technology, and to identify developments and trends in related technological topics in different countries (Mogee, 1991). According to the statistics of the World Intellectual Property Organization (WIPO), patent documents cover 95% of human scientific research achievements. Effective use of patent information can reduce the costs of R&D, shorten its time (Cantwell and Janne, 1999), and speed up R&D and inventions process (B. Jin *et al*., 2011). Due to the importance of NGH as potential alteratve energy source, major countries around the world have to started commercial exploitation of NGH. Although patent analysis is used in energy research (Assunção *et al*., 2021; Block and Song, 2022; Luan, Sun and Wang, 2021; Yin, Gu and Zhang, 2020), but it is rarely studied in NGH. This study presents patent analysis in the NGH by focusing on the following issues:

1) What are the overall patent layout in the NGH field, including time span, countries, patentees and technology classification?

2) What are the technological development trends in the NGH field from the perspective of technology topics and their evolution?

3) What is the competitive landscape in the NGH field, including national or institutional competition?

To address these issues, this study proposes a framework to monitor the developmental trend and competitive landscape of technologies related to marine NGH. First, from the perspective of patentometrics, we conducted an overall layout of patents, including the application trends, country, patentee, and hot technology area distribution. Then, based on the subject terms, the evolutionary paths of NGH related technologies are analysed, which are used to determine technological development trends. Finally, by means of correlation calculations and clustering, we analysed the competition and cooperation landscapes among countries and institutions in the key technical fields.

The general structure of this study is as follows. Section 2 describes the rules for retrieving and preprocessing of the data, as well as the methods and principles used in the subsequent analysis. In Section 3, we first provide a general overview of the patent data, then we examine developmental trends through technological evolutionary approaches, and finally we analyse the competitive landscape among countries and institutions, respectively. Finally, in Section 4, we conclude the results of this study's analysis and make recommendations.

2 Data and method

2.1 Data source and preprocessing

This study focuses on marine gas for the following reasons. Firstly, , more than 90% of NGHs occur in submarine sediments at shelf margins, and less than 10% are distributed in fractures and pores of rocks in continental permafrost (Qin *et al.,* 2022). Secondly, following a preliminary search of patents we found that the patents are mainly distributed in marine NGH related technologies. All the data in this research came from Derwent Inovations Index (DII), and since this study focuses on patent4s related to marine NGH, we added some criteria to correct the results when retrieving the data. We created the following retrieval strategy: TS = (“natural gas hydrate*” OR “gas hydrate*” OR “methane hydrate*” OR “clathrate hydrate*” OR “ch4 hydrate*” OR NGH OR “combustible ice” OR “flammable ice”) AND (“deep water” OR sea OR ocean OR offshore OR off-shore OR “off shore” OR subsea OR marine), A total of 806 patent data were obtained to 2021, using Excel and ITGInsight for analysis and visualisation of the acquired data.

2.1.1 Institutions merging

In order to eliminate data confusion and facilitate analysis, we combined institutions with different forms of expression, but belonging to the same company. For example, CHINA NAT OFFSHORE OIL CORP. In the data, there are 6 institutions whose full names are not exactly the same but have the same abbreviation, we define these data as from CNOOC and merge them. However, for universities and research institutes, we believe that there is no strong connection between sub-institutions from the same institution in different regions and they can be regarded as independent institutions, such as the research institute of the Chinese Academy of Sciences in various places, UNIV CHINA PETROLEUM HUADONG and UNIV CHINA PETROLEUM BEIJING.

2.1.2 DMCs filtering

The Derwent Manual Code (DMC), given by the Derwent indexing experts for each patented technology, is used to reveal and express the technical innovation of an invention and its applications. Past research showed that a DMC-based analysis of a patent can reveal all technology areas it relates to in detail (Aaldering and Song, 2019; Wei *et al.,* 2017). The DMCs shown in **Table 1** below were removed from the top 40 DMCs ranked by number of patents. The descriptions of many DMCs are very common (Q49-V35, D04-B07F, etc.) or too broad (Q49-E05, E10-J02D1, etc.). For these reasons, they may overwrite those DMCs with less numbers but more important or more detailed classification, resulting in unsatisfactory or inaccurate analysis. In this study, we used a filtering rule to count the top 10 DMCs sorted by number of patents, analyse the evolution of DMCs in the past 20 years, and define the technical fields of institutions and the competition between them.

Table 1 Removed DMCs

DMC	Description	Count
Q49-V35	Fluids, slurry	270
D04-B07F	Desalination of brine or sea water	28

H01-D	Producing crude oil and natural gas	25
Q49-E05	Underwater	25
H06-A02	(Liquefied) Natural gas	24
E10-J02D1	Methane	23
D04-A01	Purification of water [general]	18
H01-F	Natural gas [unclassified]	12

2.1.3 Subject terms filtering

In order to obtain the wanted subject terms, we need to perform some deletion and processing on meaningless or repeated words in records. First, after obtaining all the records of subject words, by caculating the similarity between words, we integrated the entries with a similarity value above 95.0, which means that these words represent the same meaning. Some of them used different words but mean the same, such as “riser tube” and “riser pipe”, and some of them are just words in different tenses, or the same words but in a reversed order, such as “oil production” and “ product oil”. Then we calculate the PC-value of all words, which is a method of counting the frequency of occurrence of words in all patent records and with high precision. The formula for caculating the PC-value is :

$$PC - value(a) = \begin{cases} log_2^{|a|} f(a) + 2^{|a|-2} g(a) & a \text{ is not nested} \\ log_2^{|a|} (f(w) - \frac{1}{|T_a|} \sum_{b \in T_a} f(b)) + 2^{|a|-2} g(a) & otherwise \end{cases}$$

a represents the subject word to be calculated, $|a|$ means the length of this word, and $f(a)$ indicates its frequency of occurrence in thesaurus, $g(a)$ indicates its frequency of occurrence in patent. b is an extracted candidate word that contains a, $f(b)$ means the total frequency of occurrence of b in the thesaurus. T_a is the set of extracted candidate terms that contain a, and $|T_a|$ is the count of terms in the set (Wang, Zhang and Liu, 2021a). After the calculation, we rank the subject words according to their PC-value and only select the words whose PC-value is above 1. Thirdly, by manually checking and filtering, we remove those words that were not meaningful for the analysis of this study among the words left in the previous step of screening. Such terms tend to appear numerous, frequent, and recurring in many patent data, not only confounding our analysis results, but also masking more important terms, for example, sea water, gas hydrate, natural gas hydrate, diagram, degree c and so on.

Finally, the most important step is that we used these terms that have completed the above process to generate a subject terms dictionary, which can help us limit the analysis content, refine the objects and reduce the interference with the research results in subsequent analysis. All the analyses involving subject words in this study were carried out based on the processed dictionary, rather than the fully original data.

2.2 Method

In this section, we present the main analysis methods used in this study, namely: the construction of patent relationship matrixes from the retrieved data; the determination of technology evolution paths based on the different ways in which technologies diverge; principles for determining the competitive landscape among countries and institutions; and the generation, and optimisation of visualisation graphs.

2.2.1 Patent matrixes construction

In order to construct the coorelation and cooperation networks used in the later analysis, we first need to determine the affiliation of each patent and construct an affiliation matrix for the patents. Record the order in which each research entity appears in each patent, and the order of the first occurrence shall prevail when the same entity appears multiple times in a patent. Assuming that there are *n* research entities and *m* patents, construct a matrix about the affiliation between research subjects and patents.

$$\boldsymbol{A} = \begin{pmatrix} (b_1\ \ b_2\ \ b_3)_{11} & (b_1\ \ b_2\ \ b_3)_{12} & \cdots & (b_1\ \ b_2\ \ b_3)_{1j} & \cdots & (b_1\ \ b_2\ \ b_3)_{1m} \\ (b_1\ \ b_2\ \ b_3)_{21} & (b_1\ \ b_2\ \ b_3)_{22} & \cdots & (b_1\ \ b_2\ \ b_3)_{2j} & \cdots & (b_1\ \ b_2\ \ b_3)_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ (b_1\ \ b_2\ \ b_3)_{i1} & (b_1\ \ b_2\ \ b_3)_{i2} & \cdots & (b_1\ \ b_2\ \ b_3)_{ij} & \cdots & (b_1\ \ b_2\ \ b_3)_{im} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ (b_1\ \ b_2\ \ b_3)_{n1} & (b_1\ \ b_2\ \ b_3)_{n2} & \cdots & (b_1\ \ b_2\ \ b_3)_{nj} & \cdots & (b_1\ \ b_2\ \ b_3)_{nm} \end{pmatrix}$$

In this matrix: $b_i = 1$ or $b_i = 0$, $\sum_{i=0}^{3} b_i = 1$ or $\sum_{i=0}^{3} b_i = 0$; $(b_1\ \ b_2\ \ b_3)_{ij} = (1, 0, 0)_{ij}$ means subject i is the first author of patent j; $(b_1\ \ b_2\ \ b_3)_{ij} = (0, 1, 0)_{ij}$ means subject i is the second author of patent j; $(b_1\ \ b_2\ \ b_3)_{ij} = (0, 0, 1)_{ij}$ means subject i is the third author or the author after third of patent j; $(b_1\ \ b_2\ \ b_3)_{ij} = (0, 0, 0)_{ij}$ means subject i is not the author of patent j.

Based on matrix $\boldsymbol{A}$, we can then construct the cooperation matrix $\boldsymbol{B}$ for the cooperation network. Caculate the sum of the number of patents for each subject as the first, second and third author respectively, constuct a quantity matrix $\boldsymbol{B}$ as follows:

$$\boldsymbol{B} = \begin{pmatrix} \sum_{j=1}^{m}(b_1)_{1j} & \sum_{j=1}^{m}(b_2)_{1j} & \sum_{j=1}^{m}(b_3)_{1j} \\ \sum_{j=1}^{m}(b_1)_{2j} & \sum_{j=1}^{m}(b_2)_{2j} & \sum_{j=1}^{m}(b_3)_{2j} \\ \vdots & \vdots & \vdots \\ \sum_{j=1}^{m}(b_1)_{ij} & \sum_{j=1}^{m}(b_2)_{ij} & \sum_{j=1}^{m}(b_3)_{ij} \\ \vdots & \vdots & \vdots \\ \sum_{j=1}^{m}(b_1)_{nj} & \sum_{j=1}^{m}(b_2)_{nj} & \sum_{j=1}^{m}(b_3)_{nj} \end{pmatrix}$$

In this matrix, $\sum_{j=1}^{m}(b_1)_{ij}$, $\sum_{j=1}^{m}(b_2)_{ij}$, $\sum_{j=1}^{m}(b_3)_{ij}$ represent the sum of the number of patents for subject i as the first, sencond and third author respectively.

Construct cooperation matrix $\boldsymbol{AA'}$ with matrix $\boldsymbol{A}$. Among them, matrix $\boldsymbol{A}$ is a matrix of order $n \times 3m$, $\boldsymbol{A'}$ is a matrix of order $3m \times n$, so $\boldsymbol{AA'}$ is a matrix of order $n \times n$. Assume that $\boldsymbol{AA'} = (a_{ij})_{nm}$, for every element a_{ij} :

$$a_{ij} = \boldsymbol{A}_i\boldsymbol{A}_j^{'} = ((b_1\ \ b_2\ \ b_3)_{i1}\ \ (b_1\ \ b_2\ \ b_3)_{i2}\ \ \cdots\ \ (b_1\ \ b_2\ \ b_3)_{im}) \times \begin{pmatrix} (b_1\ \ b_2\ \ b_3)_{j1}^{'} \\ (b_1\ \ b_2\ \ b_3)_{j2}^{'} \\ \vdots \\ (b_1\ \ b_2\ \ b_3)_{jm}^{'} \end{pmatrix}$$

Since the coorelation nework of this study is based on DMC, we construct the co-occurrence matrix of DMC. The co-occurrence matrix $\boldsymbol{C}$ is constructed based on research entities and DMC as follows:

$$\boldsymbol{C} = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1k} & \cdots & d_{1l} \\ d_{21} & d_{22} & \cdots & d_{2k} & \cdots & d_{2l} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{i1} & d_{i2} & \cdots & d_{ik} & \cdots & d_{il} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nk} & \cdots & d_{nl} \end{pmatrix}$$

In this matrix, d_{ik} represents the number of times DMC_k appears in the patents filed by subject A_i; n means the total number of research subjects, l means the total number of DMCs in all patents.

As the calculation of the correlations in the analysis software we used: ITGInsight, is based on co-occurrence. Therefore, finally, by matrixes $\boldsymbol{A}$ and $\boldsymbol{C}$, we can be able to obtain the correlations between the research entities and draw the relative diagrams.

2.2.2 Technology evolution analysis

By comparing the year-by-year changes in the number of patent applications in a certain technical field and studying its evolutionary process, we can see the development history of its technologies and analyse the future development trend, or to identify emerging technologies or those that are gradually being eliminated, find the weak points or hot spots in the field, and predict future research. As shown in the evolutionary map in Section 3.2, each color represents a subject term, the length of every rectangle is proportional to the number of occurrences of the corresponding subject term, and the thickness of the connection lines is related to the relationship strength between the two rectangles.

The path and direction of technology evolution can be shown by the different ways in which the rectangles are connected to each other. There are four different types of connections, representing five different evolutionary processes. First, two rectangles of the same color with only one normal line between them, means the evolution of the same technology in these two years, and the trend of increasing or decreasing can be seen, which may indicate gains or losses in importance. Second, if there is no line between a rectangle in one year and any rectangle in the next year, it means that this technology has not been used in the patent filed in the second year; If there is a rectangle that has no line with any rectangle in the previous year, it may be an emerging technology. Third, one rectangle has several lines to connect it with two or more rectangles in the following year, this means that one technology has differentiated into more technologies, and it is a refinement of it, showing the trend of further research and application, or a few technologies that are closely related to it. Fourth, several rectangles in one year are connected to only one rectangle in the next year, indicating the merger of technologies (Wang *et al.,* 2021b).

2.2.3 Competition analysis

Using the method described in Section 2.2.1, we generate a correlation network between the entities, as shown in **Fig. 1**. Each node represents an entity, the size of a node is proportional to its number of patents. The edges between the nodes represent the relationship between two entities, the thickness of which is proportional to the strength of the association, and the strength values are marked on the edges. We use the strength value in the network to represent the competitive relationship and cooperative relationship between entities. Larger strength values represent stronger connections, and vice versa.

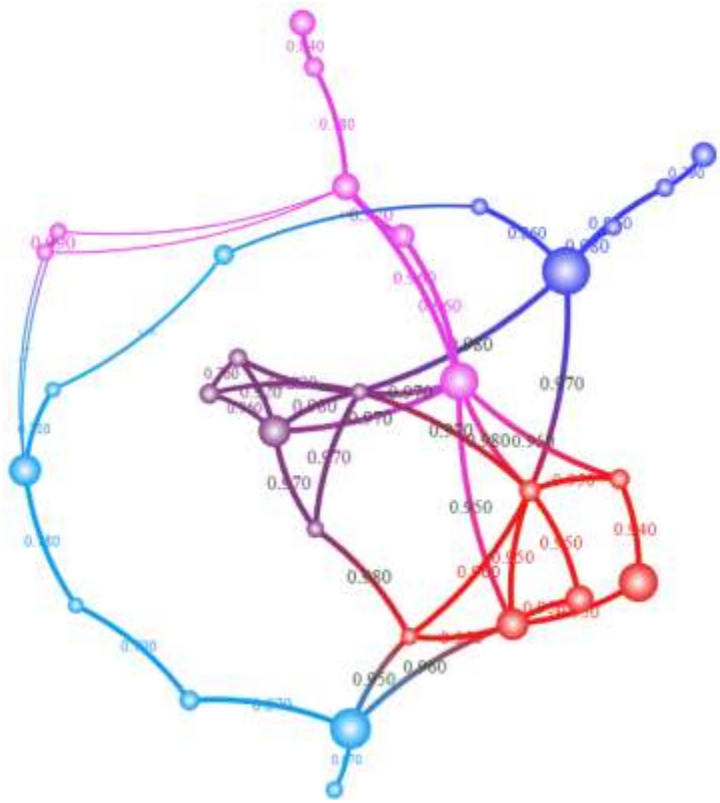

Fig. 1 Sample network of correlation relationship

Because there is less cooperation between countries on key technologies, we will only develop our analysis through the correlation network. Due to the relationship shown in the image is between countries of origin or priority, we can derive the competitive relationship between countries only through the correlation network. A node contains the patent applicants or institutions belonging to that country, and there are no cases where the same patent is filed in more than one region, resulting in a link between two regions. Therefore, we can analyse the areas of competition and the intensity of competition directly.

In contrast to countries, cooperation between institutions on patented technologies is more common, especially between institutions in the same country. Thus, we need to exclude the interference from their cooperation when analyzing the competitive relationship based on correlation networks, and we will do so by comparing the cooperation and correlation networks. If there is no line or a very thin line between two nodes shown in the former, and a thick line between the same two nodes in the latter, we can then define that there is a clear competition between the institutions represented by these two nodes. Due to our simplification of the image, isolated nodes are removed, which will result in the nodes shown in the two images generated by using the same data not exactly being the same. While we are using the rule that was mentioned above to search for competitive relationships, we may find that a node that shows a strong connection with another node in the correlation network does not appear in the cooperation network, and in this case, we can judge the existence of a competitive relationship only through the correlation network.

2.2.4 Visualisation graphs generation

We chose algorithm LinLog to complete the layout of nodes during the visualisation process. LinLog algorithm is proposed by Andreas Noack, and the energy expression of this algorithm was defined as (Esposito, 1988) :

$$U_{LinLog}(p) = \sum_{\{u,v\}\in E} || p_u - p_v || - \sum_{\{u,v\}\in V^2} \ln || p_u - p_v ||$$

In this formula, p_u, p_v represents the location of node u and node v respectively, and $|| p_u - p_v ||$ means the diatance between nodes u and v. On the right side of the equation, the first part means the attractive force between adjacent nodes, and the second part means the repulsive force between them. To avoid the situation of infinite energy, we need different nodes in different positions, and the least amount of energy represents the best layout.

After producing the desired diagrams, we need to refine and compress them further so that relationships with high correlation strength can be highlighted. There are two methods used in such a process:

(1) Using the Pathfinder algorithm. The algorithm was designed to analyse data similarity in 1990 by American psychologist Schvaneveldt, Durso and Dearholt (1989), by keeping the strongest connection among all possible paths between two nodes after checking the association between all data, by establishing the most efficient connection path.

(2) Setting a threshold. By choosing a suitable value as the threshold, we can make the visualisation only show the lines that exceed the set threshold. This approach offers us a way to improve the image that is not only simple but also easy to understand and interpret. The image can also be adjusted flexibly according to different datasets to meet the needs of different analysis. By filtering out a part of the connection in this way and re-layouting it, the image can be further optimized.

2.3 Research Framework

We integrate the methods mentioned above into the following research framework in **Fig. 2**.

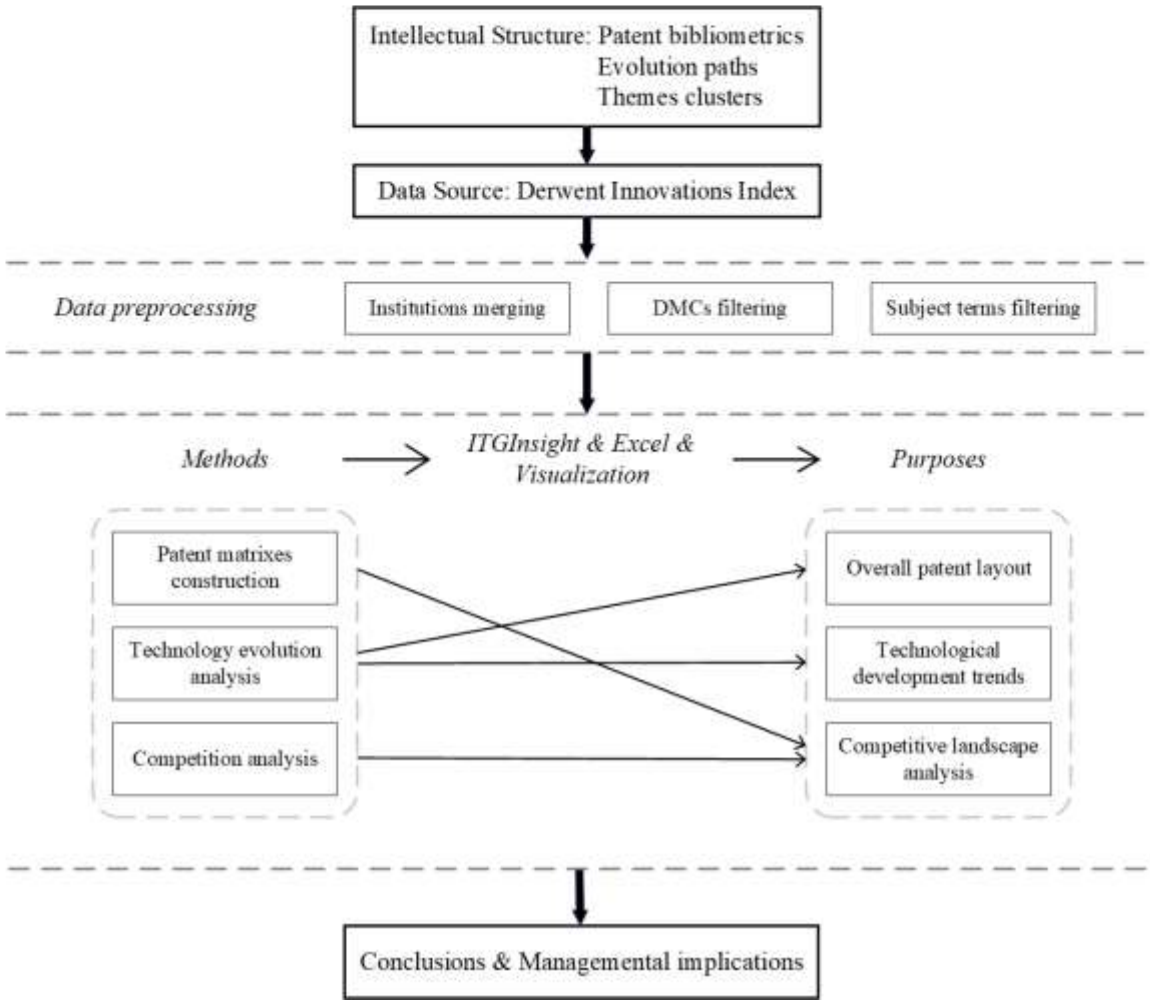

Fig. 2 Research framework

3 Results and discussion

In this section, we will analyse and discuss the results from the following three perspectives: a general overview of patent data, trends in technological evolution, and an analysis of the competitive landscape.

3.1 Overall patent layout

In order to obtain a comprehensive overview of patent layout and filing trends, we analyse the patent data and discuss the results from four perspectives: temporal, geographical, patentee and technology classification, respectively.

3.1.1 Time span analysis

The trend of the number of patent applications over time can only reflect the development trend of scientific and technology innovation in a research field, but also the active degree of its innovation. We counted the number of applications by year for the patents retrieved, as shown in **Fig. 3**. **Fig. 3** shows that the technologies related to the patent of marine NGH have been developed since 1967. In 1967, the first patent application was made by SHELL OIL CORP of the US. **Fig. 3** also shows the annual change in the number of global patent applications in the field of marine NGH. As can be seen, the technologies for these have been developed since 1997. The intuitive reason may be that Kyoto Protocol, which was developed by international climate organisations in 1997, a decade-long development of emerging alternative energy sources was spawned. After a brief surge in 2006, there has been sustained and significant rapid growth since 2015, and reached the peak for patent applications in 2020. Possible explanations for this apparent increase is that in 2016, the Paris Agreement called for a "global average temperature increase of less than 1.5°C by the end of the 21st century" (UNFCCC, 2015). This attributes to the increase in research over the last five years, as a bridge energy for the transition from fossil fuel to energy, NGH is a focus of attention for all parties.

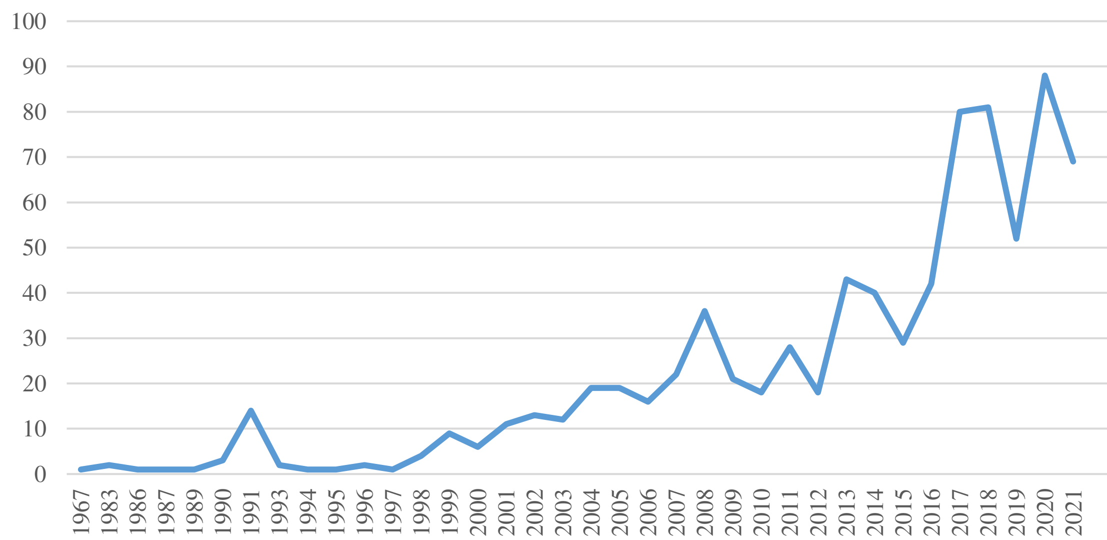

Fig. 3 Global patent application trend of marine NGH patent technology

3.1.2 Geographical analysis

Over the past 20 years, the number of patent applications for marine NGH has continued to rise. Since 2021, more than 30 countries or regions have applied for related patents. In order to reveal the trend of the major patent application countries and forecast changes of related technologies in the global market, we chose the top 10 countries to draw the evolution map. Considering that many countries may apply for patents in WIPO, we removed it from the data records, and merged data belonging to Russia and the Soviet Union. Each color represents a country; the country's name is marked on the rectangle using an abbreviation; and the length of the rectangle is proportional to the number of patents applied for by the corresponding country.

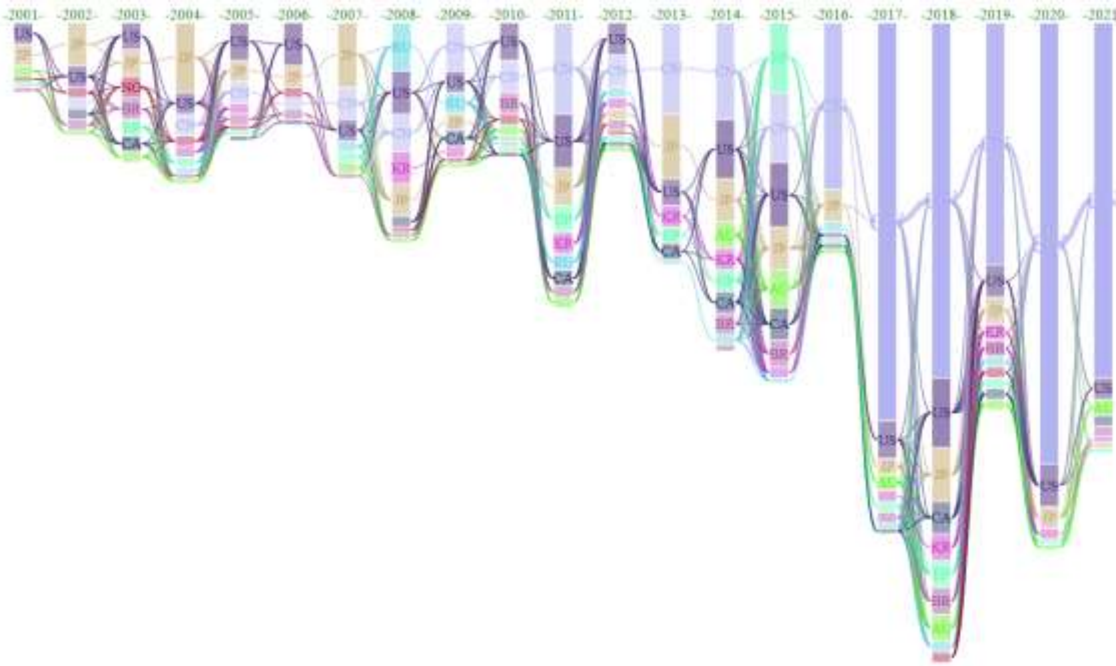

Fig. 4 Evolution map of the top 10 countries in the past 20 years

As shown in **Fig. 4**, the number of patent applications in the US has maintained a steady growth rate with a slight decline in recent years, and reached a maximum of 13 in 2018. With an abundance of fossil energy, the need for NGH in the US is not in demand. USA has perfomed three mining tests of NGH with Canada. In recent years, the US has invested less in NGH research but continues to surpport basic science research and participate in major international hydrate programs. In contrast, due to the lack of energy resource, Japan attaches great importance to the investigation and exploitation of NGH. Japan's NGH R&D plan for the 21st Century, which began in 2000, covers all aspects of NGH exploration, development, environmental impact, as well as engineering options for offshore mining and commercialization studies. The search for safe and reliable energy has always been a top priority in Japan's national energy policy and innovation policy, and NGH have once again become a hot topic following the nuclear power plant incident in Fukushima in 2011. It has conducted two NGH exploitation tests in the Nankai Trough in 2013 and 2017 (Zhu *et al.,* 2020). However, neither of the two field test in 2017 resulted in significant production increases , and the number of patent applications in Japan has also show a downward trend in the past 3 years.

The number of patent applications in China was a relatively small part of the global total until 2010. It start to grow steadily from 2011 to 2014, and has risen significantly from 2015. Since 2015, the annual applications have accounted for more than half of the global total. It reached a peak of 82 applications, accounting for 92% of the annual global application volume in 2020. The number of Chinese patents in the last six years is surging. There are two reasons for this. Firstly, it is due to the confirmation of a super 100 billion cubic metre gas hydrate deposit in the Shenhu sea area in 2015 and the identification of hydrate drilling targets in 2016 (Tan, Pan and Liu, 2016). Secondly, according to the *The Report of China Mineral Resource Reserves, 2018*[1], the preliminary forecast for gas hydrate resources in China's

[1] http://en.cgsjournals.com/article/doi/10.31035/cg2018100

waters is about 8×10^{10}t of oil equivalent, which is equivalent to more than half of China's total onshore oil and gas resource.

3.1.3 Patentee analysis

As shown in **Fig. 5** nine of the top ten institutions come from China. It shows that although China started late in the field of marine NGH, it has caught up with other countries in terms of the number of applications. These institutions mainly come from universities and research institutes, which means that the marine NGH are still in the basic theoretical research stage. However, the number of patents held by the enterprises cannot be ignored, representing that some technologies have already begun to be commercialized in recent years. Because of this study limits the technical direction to marine NGH and mainly focus on its exploitation. Although there are many patents related to the transportation and manufacture of NGH, or the study of NGH in permafrost areas, these have not been retrieved.

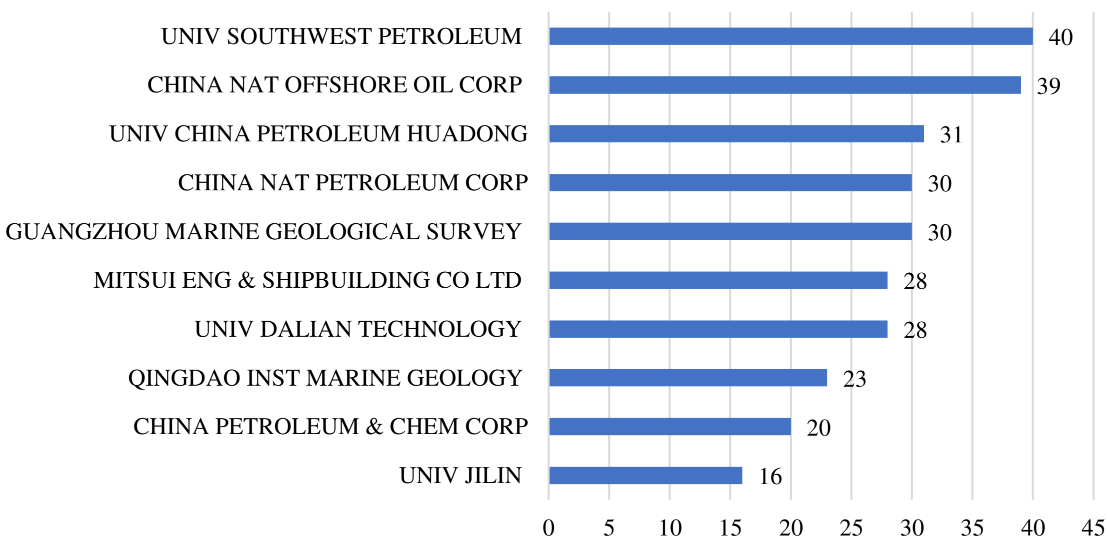

Fig. 5 Top 10 institutions for patent application

3.1.4 Technology classification analysis

We selected the top 15 DMCs and as shown in **Fig. 6**. H01-D08, H01-C03, and E31-N05C are three different mining methods: thermal injection, depressurisation, and CO2 replacement. Q49-A, H01-B01, H01-D05, Q49-A01, H01-B03C3, H01-D04, H01-B03C3, A12-W10A, H01-D03, and H01-C01 are all related to the equipment and components exploited in the NGH field. From a broader category of DMC, the results show that the patents of marine NGH are mainly concentrated in the fields of H01 (Obtaining crude oil and natural gas – including exploration, drilling, well completion, production, and treatment) and Q49 (Mining). Therefore the research topics are generally related to technology and equipment of drilling and mining for NGH. The top 15 DMCs with the number of patents and their meanings are shown in Table A1 in Appendix.

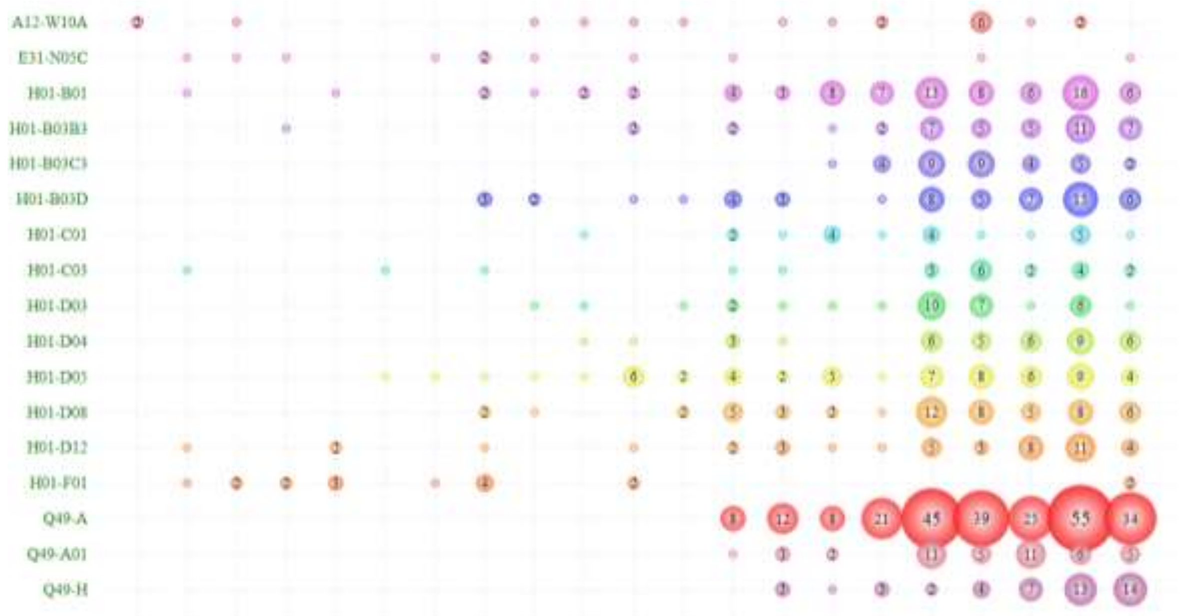

Fig. 6 Evolution map of the number of major technology patents in the last 20 years

Fig. 6 shows the changing trend of the number of patents for different DMCs in the past 20 years. Some technologies were applied for related patents over a long period of time. The annual number of patent applications remains basically stable, and has a high frequency of occurrence, such as A12-W10A, H01-D05, and H01-B01. This shows that they have received attention over a long time as basic mining equipment or method. On the contrary, we can see that only the patent number of H01-F01 are declining. From 2012 to 2020, there has been no patent application. This means that this DMC mainly involves the traditional on-site processing technology of NGH rather than mining processes. There are some technologies that have not been patented before, or have been in small number , but gradually developed in recent years, such as H01-B03B3, Q49-A, Q49-A01, Q49-H, H01-B03C3, H01-D08, H01-D03, and so on. All of these indicate that the multiple mining methods of NGH have begun to receive widespread attention and utilisation.

3.2 Technological development trends

Because of the importance of patents in the last twenty yeaes, we chose the evolution of subject terms to reveal the evolution process of patent topics and reflect technological development trends over time in the marine NGH field. After deleting some terms that appear many times but have no actual research significance, we selected the top 40 subject terms with the highest frequency of occurrence to make the evolution map in the past twenty years as shown in (**Fig. 7**), and grouped them according to different technical topics and conducted an analysis for each topic.

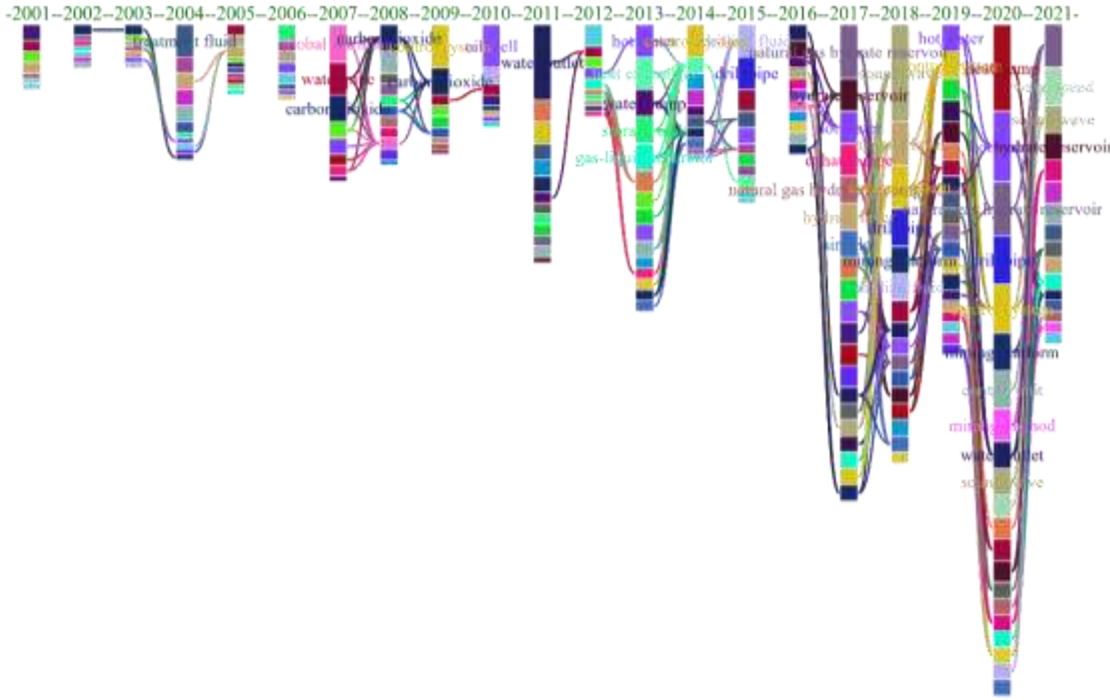

Fig. 7 Evolution map of subject terms

As shown in **Fig. 7**, we can see that the technical aspects of marine NGH are broad. Before 2007, the technology focus was not the same, and there were constantly substituting with only a few of them being intermittenly linked. It was similar between 2009-2012 and 2015-2016. Since 2016, we can see that the intersections among technologies become significant. In the following, we will analyse the developmental trends of these technology topics in detail by grouping the subject terms.

3.2.1 Evolution of mining methods

(1) CO2 replacement method

The principle of this method is that CO2 is used to displace NGH and store in the original NGH reservoir (Lee *et al.,* 2017; Wang *et al.,* 2015). Since CO2 is more readily form hydrates than methane, this method is very useful to reduce greenhouse effect. However, the replacement method is less commercially available due to the constraints of low replacement efficiency, but it has always been a popular research topic (Wang *et al.,* 2021a).

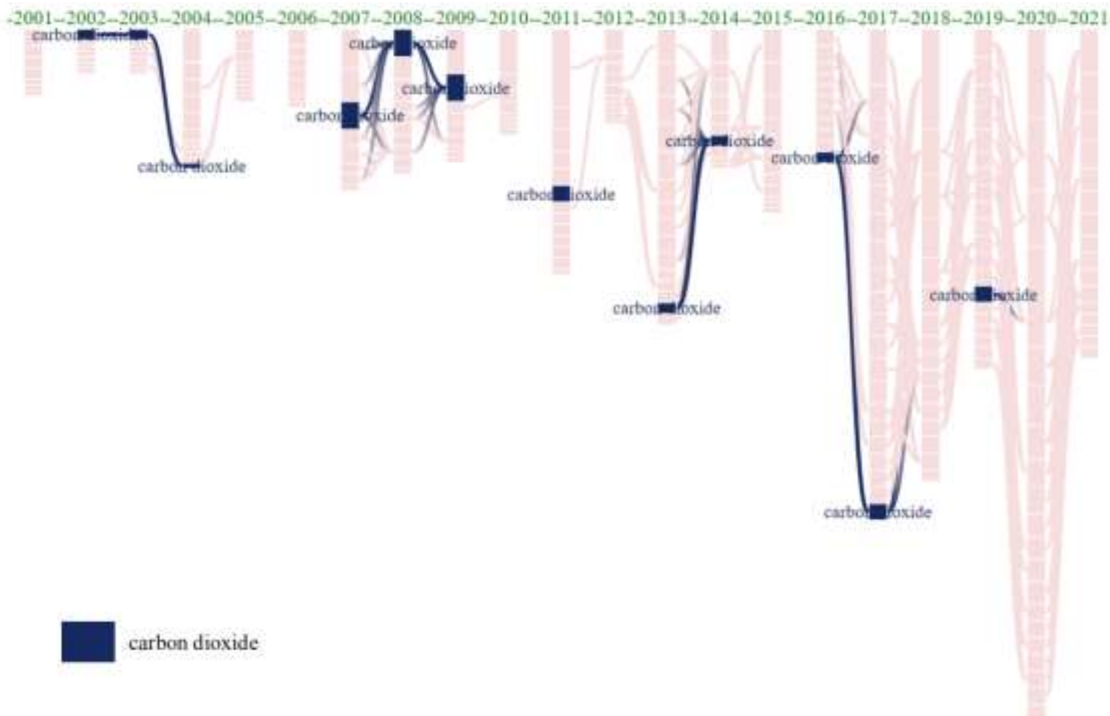

Fig. 8 Evolution of CO2 replacement

In **Fig. 8**, we can find that the technology of CO2 replacement mining has been patented early, and has consistently appeared over the last 20 years. The number of patents stayed at a steady level and did not fluctuate much, and was at its highest share from 2007 to 2009. It suggests that this technology has not made some significant progress. Compared to before 2015, the number in recent years has shown a slight decline which means that this method is not yet commercially available for NGH extraction. Therefore, the use of this method is gradually decreasing with the development of other mining techniques.

(2) Thermal injection

The principle of this method is that the heated mediums (e.g., hot water, microwave, electromagnetic wave) are injected in NGH reservoir to break the equilibrium of the hydrate phases and induce hydrate decomposition (Shi *et al.,* 2021). As a mining technology in an early appearance, the thermal injection method has been used in the field of NGH mining for a long time, as shown in **Fig. 9**. The thermal injection method can avoids secondary NGH plugging which can serve effectively as an auxiliary method (Li *et al.,* 2016; Liu *et al.,* 2019). However, it is understood that the efficiency of using the thermal injection alone is not considerable, thus it is rarely used individually (Kumar *et al.,* 2019). Generally, it is used in conjunction with other mining methods as a means to induce rapid decomposition of hydrate reservoirs.

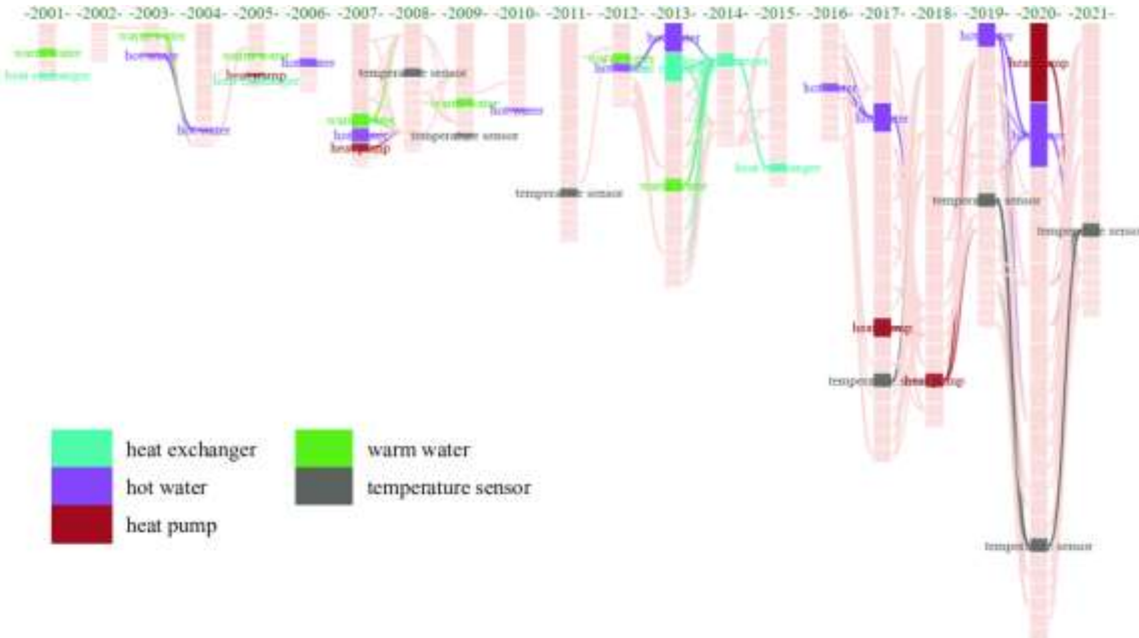

Fig. 9 Evolution of terms related to thermal injection

In **Fig. 9** we can see the two terms "hot water" and "warm water", which means the same, occured many times during the past 20 years. Moreover, there are many evolutionary links between these terms and other terms in recent years. The meanings of which are not shown in the map, such as "gas-liquid seperator", "global warming", indicating that they cannot be judged from their literal meaning as part of the thermal injection method. Although we know the use of thermal injectionhas low efficiency, but the evoluton map shows that its use has not diminished as the number of patents has increased in recent years. However, there has been an increase in the number of occurrences of "hot water" and "heat pump" in 2020. From those terms, we find that there are many edges between the terms related to thermal injection and terms related to other techniques. For example, "carbon dioxide" and "sound wave". The result illustrates the crossover of the thermal injection method with a variety of other methods.

(3) Depressurisation method

The principle of this method is that when the hydrate pressure drops below the equilibrium pressure by means of groundwater extraction or gas lift, it automatically decomposing NGH from the hydrate reservior (Wang *et al.,* 2018; Zhao *et al.,* 2015). Due to the simplicity of the operation, high energy efficiency, and the relatively rapid induced decomposition (Moridis *et al.,* 2011), the depressurisation method is considered to be the most economical and effective NGH mining technique (Aghajari, Moghaddam and Zallaghi, 2019). However, this method may lead to low temperature and freezing of the hydrate reservoir, and the secondarily formation of hydrate will block gas channels and affect the production efficiency (Li *et al.,* 2021). In recent years, in order to increase the yield of NGH, there has been research on mixed mining methods that combine depressurisation with other auxiliary means such as, the hydraulic fracturing (Feng *et al.,* 2019), the thermal injection (Cranganu, 2009; Su *et al.,* 2013).

Next, we select these terms in **Fig. 10** into the same group to study and analyse the evolution of this method. There are two exceptions to the choice of these terms. Firstly, in the chemical reagent injection mining method, although it decomposes the hydrate reservoir, the lack of relevant patents results in few terms associated with this method. Secondly, in the solid fluidised mining method, its decomposition occurs in pipes or on sea surface because of the "in-situ fragmentation" technique (Zhou *et al.,* 2018), but the "decomposition" in **Fig. 10** are mainly linked with terms "hydrate layer" or "hydrate reservoir" that do not belong to the solid fluidised mining method. Therefore, the terms in **Fig. 10** we choose do not fall into the above two mining methods.

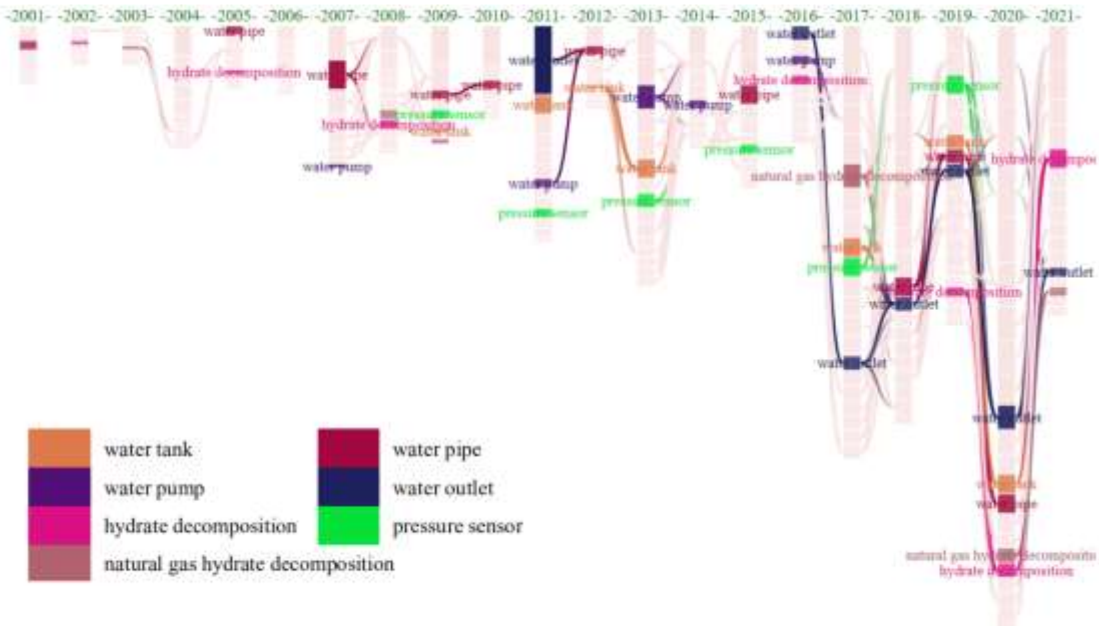

Fig. 10 Evolution of depressurisation

As shown in **Fig. 10**, although depressurisation method is a relatively simple and mature mining technique, it has not been used much in the field of marine NGH extraction before 2017. This suggests that at an early stage, marine NGH extraction received less attention. From 2007, the number and type of occurrences of related terms began to increase, and terms like pipe, pump, tank, etc. that involved basic installations and methods have appeared almost every year since 2009, maintaining a steady and gradual growth. In 2017, 2018, 2019 and 2020, the total number of occurrences of all terms relating to depressurisation method is 16, 7, 15, and 19 respectively. This shows that although the number and variety of subject terms has increased, the number of occurrences of terms related to this method has maintained a relatively stable trend. This suggests that as a mature mining technique, the achievements have remained satisfactory after being put to use in the extracion of marine NGH.

The two terms "hydrate decomposition" and "natural gas hydrate decomposition" are always connected with more terms in recent years. However, we can see a very low number of occurrences of these two terms prior to 2016, there were even 10 years in which these words had not appeared. The rarity of connecting lines suggesting that previously there was less exploitation of marine NGH. On the contrary, the increace in the number of occurrences in recent years after 2016, which indicates that the ways and means of promoting the decomposition of marine NGH have gradually begun to develop and progress, and there are more related technologies and equipment.

(4) Solid fluidised

The principle of this method is to break down the NGH reservoir directly into granular form, then transport the flow that contains the solid particles to the offshore platform for further hydrate decomposition (Zhou *et al.,* 2014). This method does not change the equilibrium of the marine NGH layer and avoids the massive and disorderly decomposition of NGH on the seabed, which can ensure the stability of geological and ecological environment. Thus, it has the characteristics of safety, high efficiency, and environmental friendliness (Wang *et al*., 2022; Zhao Jinzhou and Na, 2017). Besides, the marine NGH reservoirs located in the Shenhu sea in China are non-diagenetic ore bodies. Due to its special characteristics, this method is more effective compared to others. China conducted the first successful test mining using the solid fluidised method in 2017. (Shouwei *et al.,* 2018).

As an emerging technology in recent years, the solid fluidised method has a relatively small number of patents associated with it, and the relevant subject terms do not appear in **Fig. 7**. However, its excellent characteristics and the developmental potential of marine NGH test mining cannot be ignored. Therefore, in order to study its development process and trend, we conduct an evolutionary analysis of the subject terms related to this method separately. We added to the original retrieval strategy: ("solid*" AND "fluid*"), and gained 14 patent records related to the solid fluidised method and. Through the processing method of subject terms in Section 2.1.3, we generated **Fig. 11**.

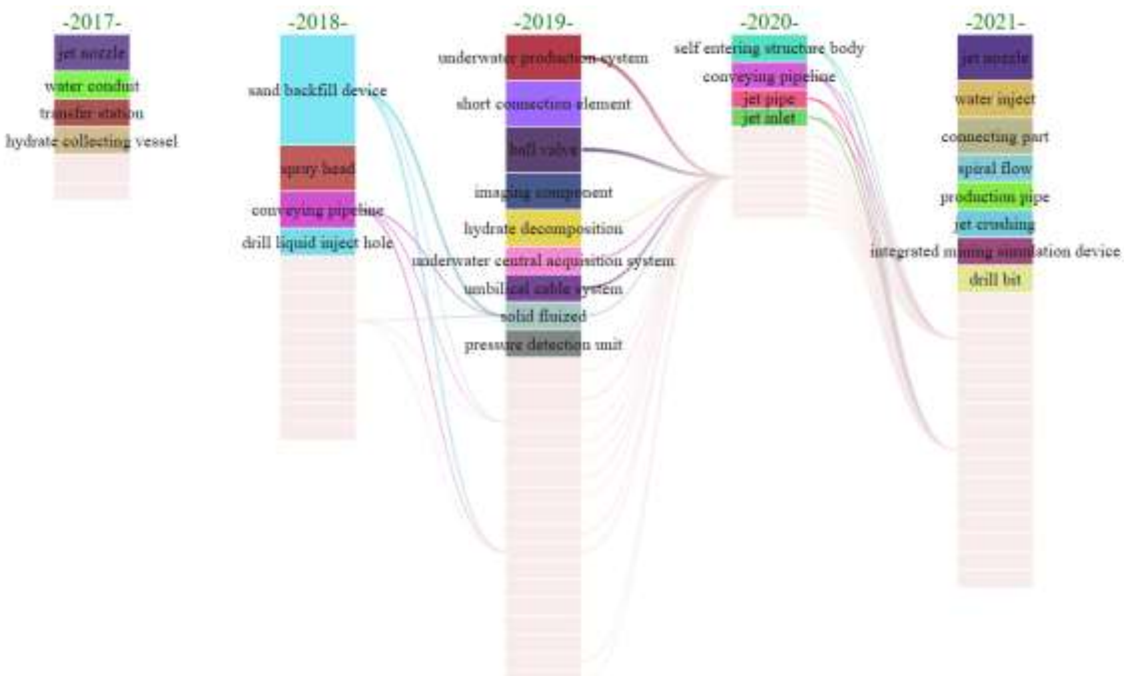

Fig. 11 Evolution of solid fluidised

Fig. 11 shows the more frequently occurring subject terms in each year, which are used to analyse the changing focus and developmental trends of technologies related to the solid fluidised method. In 2017, when this method first emerged and was first put into test mining, the patents related to it mainly focused on the various types of equipment used in mining by this method. Then, in 2018, subject terms that appeared more frequently were about “sand backfilling” and conveying. This indicates that researchers are beginning to focus on the transport of the acquisition and the backfilling of the NGH reservoir after implementing the extraction. In 2019, the categories of subject terms began to increase, covering a wider range, including underwater mining and production control systems, monitoring units, image content, cables, etc. This shows that research on the use of this method in marine NGH mining is progressing, and the relevant facilities in NGH reservoirs suitable for production by this method are gradually improved. Although there are fewer patents in 2020, for the first time, the terms "drilling cost", "drilling efficiency", and "geological disaster" appear in relevant patents, indicating that experts are beginning to pay attention to the costs, efficiency, and the impact on the ecological environment during the mining process. Finally, in 2021, patents begun to focus on various modules and equipment of integrated extraction systems, reflecting the fact that the method is being put into test mining.

3.2.2 Evolution of other technologies

(1) Exploration technology

The exploration technologies used in marine NGH mainly include seismic reflection, electromagneitism, logging, borehole sampling, and so on (Sadeq *et al.,* 2018). In **Fig. 12**, two terms "sound wave" and "wave speed" represent "acoustic technique", which is one of the seismic reflection techniques and widely used in subsea energy exploration (Winters *et al.,* 2007). This exploration technology is widely used for discovering NGH reservoirs since 2016.

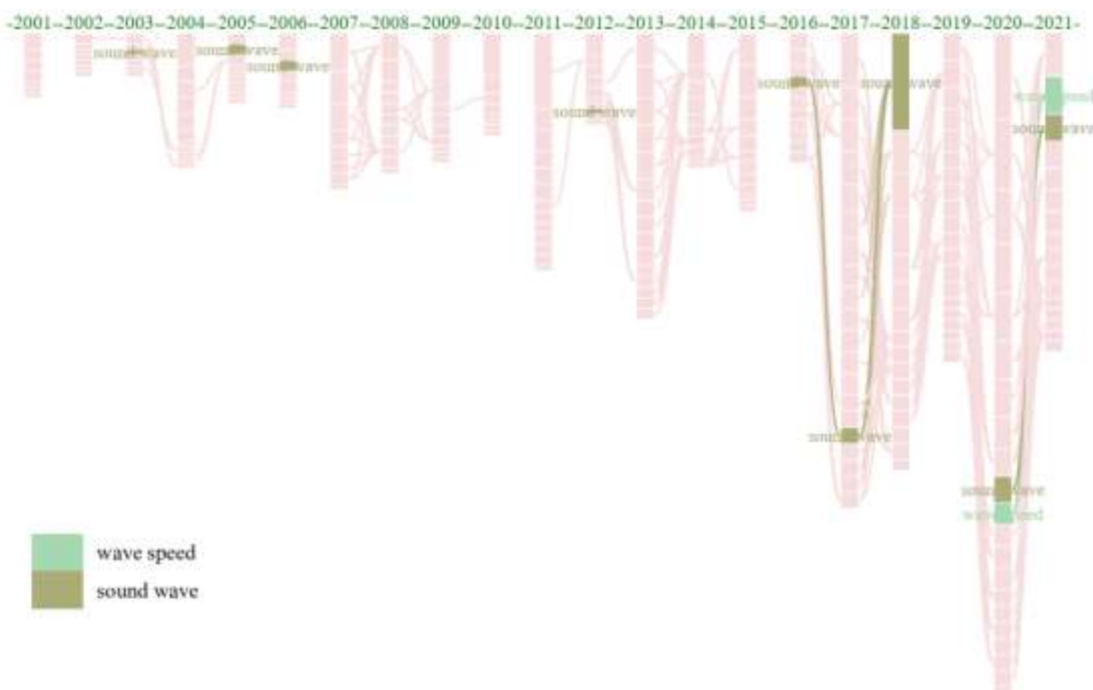

Fig. 12 Evolution of exploration technology

(2) Control system

In **Fig. 13**, two terms "control system" and "control unit" span a long period of time, and the number of occurrences of them varies slightly from year to year. We define them as control system during the process of mining NGH. The exploration and mining of marine NGH are carried out by remotely controlling machines or equipment on the seafloor. In NGH research, , the control system receives and transmits signals through the control unit used to feedback the sound, vibration, temperature, etc. of the seabed, so as to allow the manual or automatic control of the equipment by the operator.

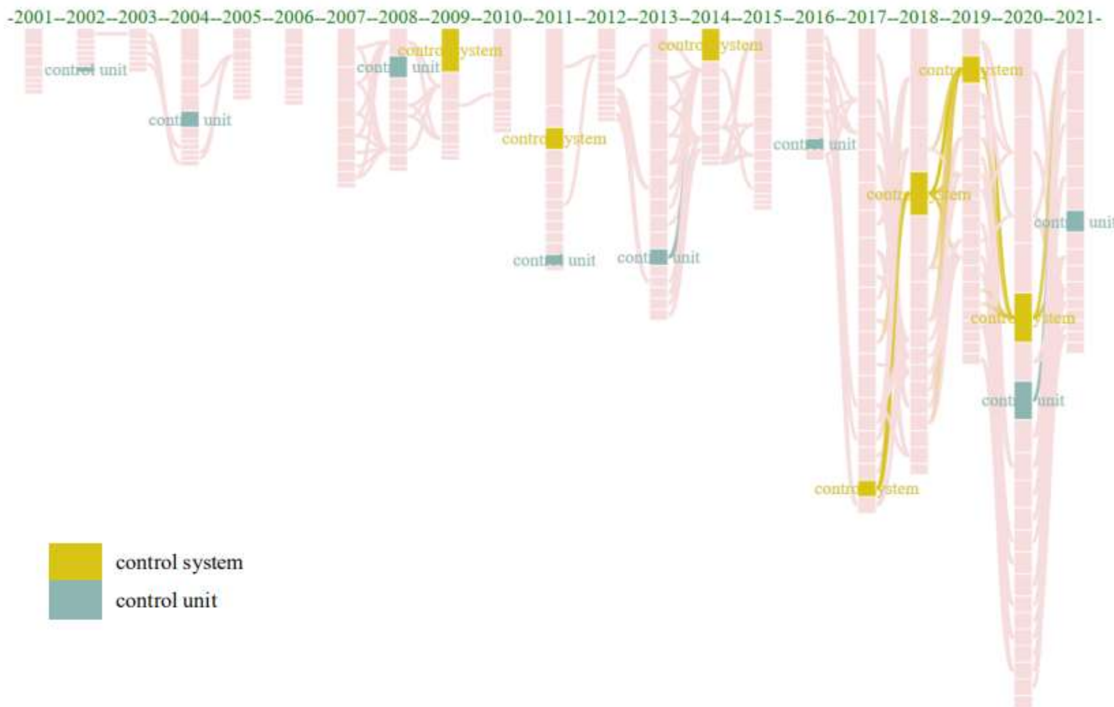

Fig. 13 Evolution of control system

(3) Infrastructure and equipment

We classed all the terms that related to digging, drilling, and mining into infrastructure and equipment, as shown in **Fig. 14**.

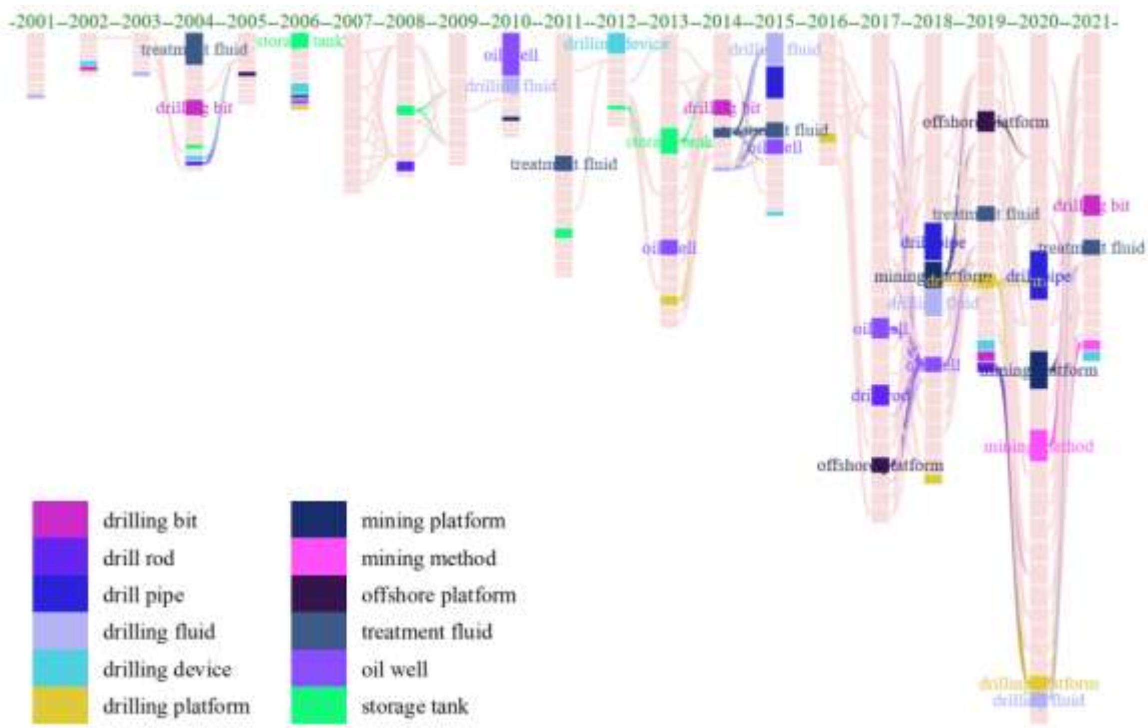

Fig. 14 Evolution of mining devices

Similar to the evolution of control system, these terms also have a long time span, and the technology evolution of these basic devices has been modest, and the general trend has remained stable before 2014. However, with the rapid increase in the number of Chinese patent applications and the fact that China's main research and exploritation areas are located in the South China Sea, the number and type of these infrastructures and tools in the field of marine NGH has began to grow after 2014.

(4) NGH reservoir

We set terms "hydrate reservoir", "natural gas hydrate reservoir", "hydrate layer" and "natrual gas hydrate layer" into one category and carry out evolution analysis in **Fig. 15**.

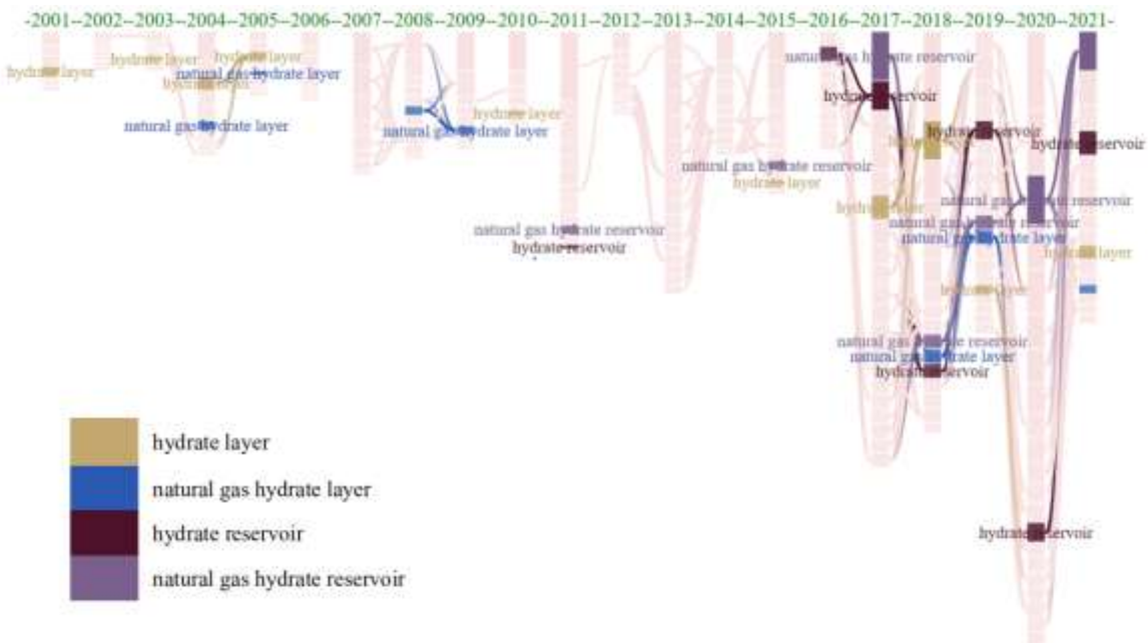

Fig. 15 Evolution of NGH reservoir

In **Fig. 15**, there are two sets of terms indicating NGH reservoir, one is composed of layers: hydrate layer and natural gas hydrate layer. The other is composed of reservoirs: hydrate reservoir and natural gas hydrate reservoir. Allthough these two sets have the same meaning, the evolution trends they show are opposite. For "layer", which appeared early and frequently before 2010, has almost disappeared with only two prominent occurrences in recent years, 2017 and 2018. On the contrary, "reservoir" did not appeared from 2001 to 2014, except for a brief appearance in 2011, and only in 2015 did they begin to emerge consecutively, with a more significant number of occurrences in recent years. The evolution trend of two terms with the same meaning is reversed. This situation occurs for the following reasons:

First of all, among all the retrieved patents, we found that majority of those using the word reservoir" are Chinese institutions, while the description "layer" is used mainly by institutions in other countries. It can be seen that NGH has been a research hotspot for decades, whereas China has only started to pay attention to this in the last five or six years, and the technology is lagging behind. But in recent years, with investment in R&D and patent applications, its development momentum is very strong and the speedy. In the period from 2006 to 2014, both pairs of words appear infrequently. We speculate that it may be that in an environment where the energy crisis was not severe or where there was insufficient awareness of the crisis, there was insufficient investment and motivation in R&D due to the difficulty of extraction, resulting in less research on the exploration and extraction of hydrate layers and reservoirs.

3.3 Competitive landscape analysis

3.3.1 National competitive landscape analysis

This section analyses the competitive landscape of key technologies from two angles. We first analyse the main technology and competitive areas among countries based on the DMC, and then we analyse the competitive landscape in the different technology areas based on the subject terms.

(1) Main Technical Fields

In order to demonstrate the strengths and weaknesses of each country in popular technology areas, we use the top 10 countries to show the distribution of their respective patents applications in the top 15 DMCs and generate **Fig. 16**. Each color represents a DMC marked below the diagram, the width of the rectangle is proportional to the number of patents under the DMC corresponding to that color.

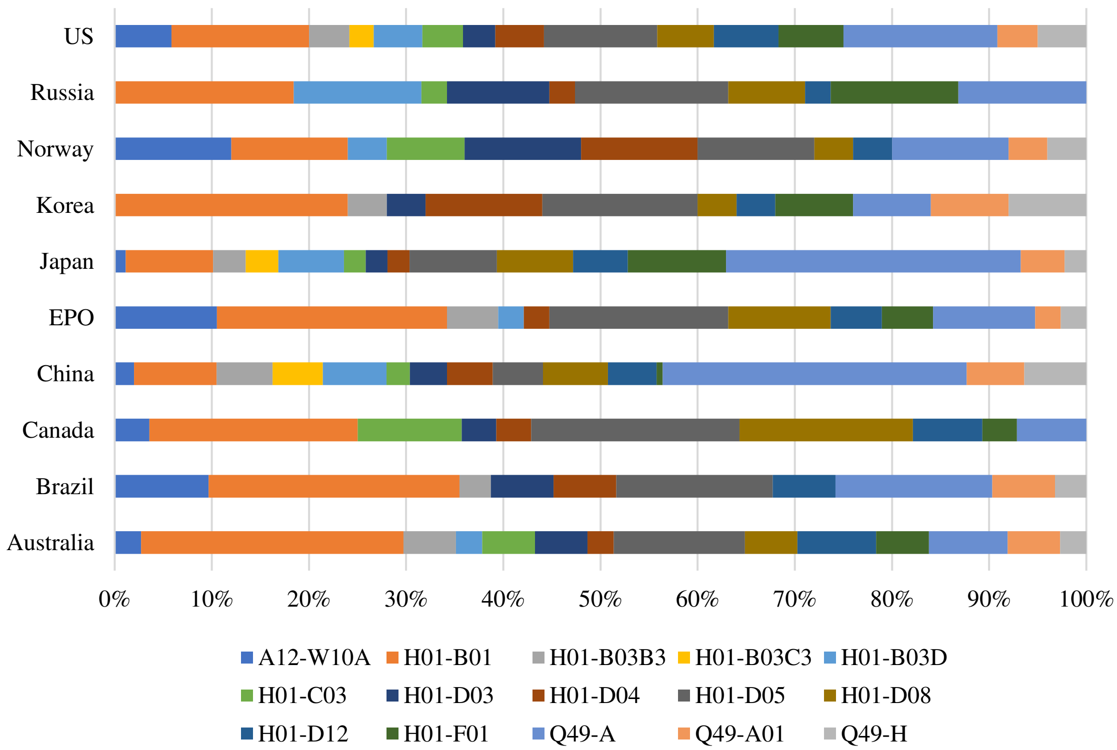

Fig. 16 Distribution of patent technology themes in major countries

It is clear that each country has its own areas of technological strength in NGH. From a proportional point of view, US patents have the most balanced distribution of technology themes and are more advanced in many of the technologies. Both China and Japan have a high percentage of patents on Q49-A. Canada does not hold a large number of patents in total, but has the highest percentage of patents in H01-D08 of any country, as do Korea, Norway and Australia in H01-B01.

Meanwhile, some countries' areas of technological strength do not fully encompass all popular technology areas, or have more obvious disadvantages. For example, neither Russia nor Korea has a patent related to A12-W10A, the EPO does not have a patent related to H01-D12 while all other countries do. Canada has obvious areas of strength but also obvious weaknesses in that it does not cover a wide range of technology areas, as does Russia, which covers only 10 of the 15 DMCs. Some technologies are only mastered by a few countries, such as the US, Japan, and China, which have patents related to H01-B03C3, and in addition, only these three countries have patents on each of the popular technologies, which shows a possible competitive relationship between them.

(2) Country competition analysis

Each DMC represents a corresponding technology, so it can provide a clear and accurate technology classification for patents in the field of marine NGH. Therefore, based on the DMC, we can not only identify popular technology areas, i.e., those with a high number of patent applications, but also analyse which technology areas are in competition among countries.

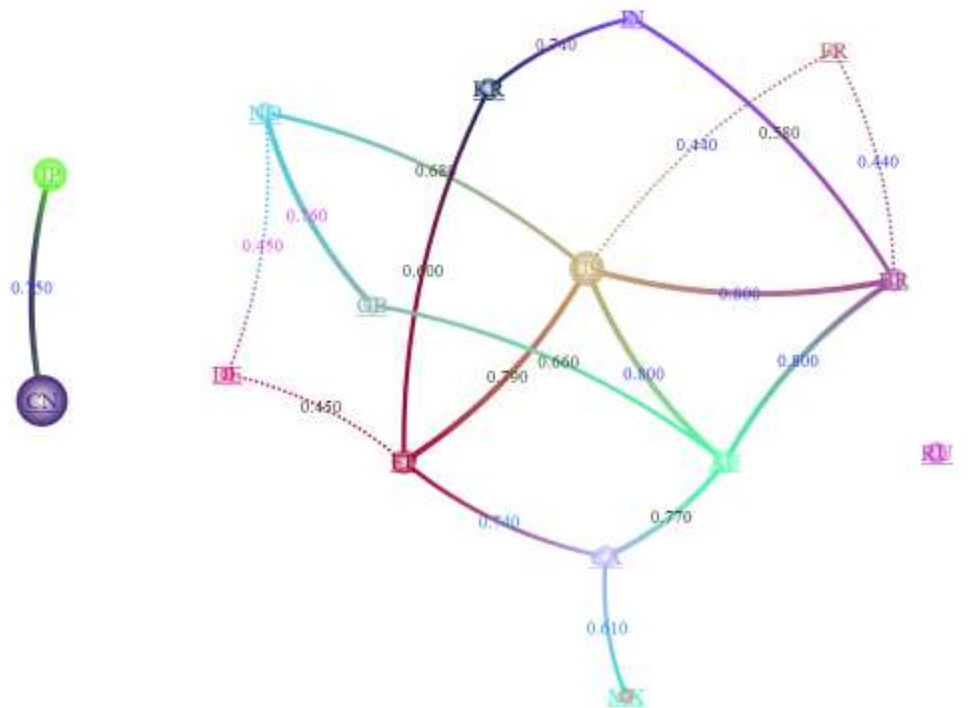

Fig. 17 DMC-based country correlation network

Based on patent matrixes construction in Section 2.2.1 and visualisation graphs generation in Section 2.2.4, we obtain **Fig. 17**. We can see that the correlation network is divided into three parts: the middle part is the more densely connected, with the United States as the centre; the left part with only two countries, China and Japan; and the right part with Russia, which is not connected to any country. There are 8 pairs of countries in **Fig. 17** with a correlation strength of 0.75 or more, reflecting countries' that are interested in technology R&D and patent applications in NGH

On the left side of this network, both the Nankai Trough in Japan and the Shenhu Sea in the South China Sea are among the five hydrate test areas in the world, and Japan has been investing in the exploration and extraction of marine NGHs in its South China Sea Trough area since 1995. In 2015, china discovered that there are over 100 billion cubic meters of NGH deposits in the Shenhu waters, and mining technologies have developed rapidly, resulting in the surge of patent applications. Because the test mining areas of the Japan and china are similar, their respective mining techniques and methods must also intersect, thus creating competition in these areas. The strength value of the correlation between China and Japan is 0.75, which also confirms the existence of a more intense competition between the two in marine NGH. After comparing the DMCs with a large number of patents in these two countries, we found that they overlap in DMCs Q49-A, H01-B01, H01-D05 and H01-D08, i.e. the main competitive technology areas. These technologies are mainly related to various types of production equipment and mining methods in NGH .

As a country at the forefront of NGH research in the world, the US is actively participates in major international NGH programs as shown in the middle correlation network. Therefore, it has a correlation with many countries. By examining the main DMCs, we found countries, such as Australia, British, and Norway, have a high number of patents related to A12-W10 (Mining, oil wells), A12-W10A and A12-W10B (Well stimulation, flooding, recovery, fracturing). Within this network, it can be seen that these countries have a high number of correlations, with most of them being connected to two or more countries, such as EPO, Brazil, and Canada. This illustrates the diversity of competitive relationships within this network. There are also multi-perspective correlations in this network. The triangular network formed by the US, Australia, and Brazil, has the highest association than the quadrangular network formed by the US, Australia, Canada, and EPO.

It can also be seen that, the competition between China and Japan, and the competition centered on the US, are different in the technically. In the middle competition network, in addition to the US, Australia is also highly competitive.

(3) Country cluster analysis

When it comes to identifying technology areas, the classification method of DMC, while having considerable accuracy, but suffers from coarse granularity and a lack of detail and specificity. Though individual subject terms have limited expression content and are better in distinguishing technical fields, the combination of multiple highly relevant subject terms can show the corresponding technical field more precisely. Therefore, to compensate for the incomplete presentation of specific competition areas and the lack of detail in the above correlation analysis, we will further show the competitive landscape of countries in various technologies through clustering based on subject terms.

We classed all patents based on the thesaurus of subject terms generated after previous filtering in **Fig. 18**, and the remained of the 790 nodes after deleting the irrelevant patents. In this map, countries were distinguished by the color of the nodes, and clusters were distinguished by the colour of the density map, and each cluster was numbered in the middle, as shown in **Fig. 18**. The subject terms with a high number of occurrences in each cluster were exported, as shown in **Table A2** in Appendix.

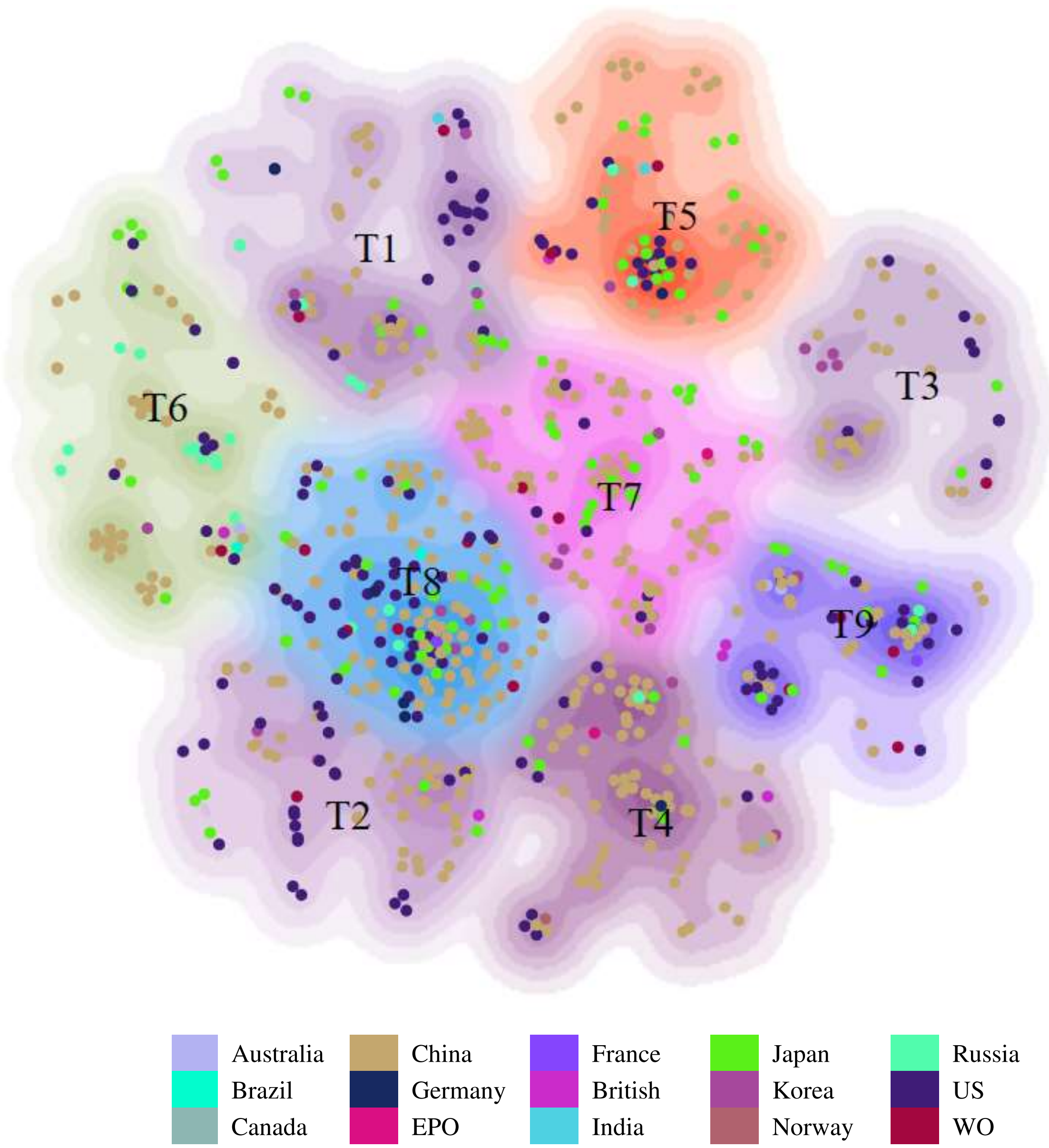

Fig. 18 Subject terms-based cluster scatter plots map

As it can be seen in **Fig. 18**, the key technologies in marine NGH field are concentrated on nine areas. **Table 2** presents the results of the summary of the main subject terms in each cluster to determine the technology area they each indicate,

Table 2 Technology areas

Cluster	Technology area
T1	Depressurisation mining method
T2	Chemical injection mining method
T3	Replacement mining method

T4	Drilling structures and related equipment
T5	CO2 replacement mining method
T6	Drilling platforms
T7	Hydrate layer extraction and gas transmission
T8	Drill fluid and injection
T9	Thermal injection method

In terms of the density of nodes, a higher density indicates a higher number of patent applications in that technology area, which is a popular and critical area where many countries are conducting relevant R&D and competing with each other. For example, as can be seen from the colors of the density map in **Fig. 18**, the nodes are dense and there is a wide variety of node colors in T8 and T9, indicating that the transport of marine NGH and the thermal injection method are widely researched and applied, the related technologies are mature. These are the centers of competition between countries, and the main competitors in both clusters are China, the US, and Japan.

The clusters with low node density, indicate that the competitiveness of each country in this area is relatively low and that the relevant technologies they possess are not yet comprehensive. For example, in T2 and T3, of **Fig. 18**, the practical difficulties of applying the replacement method and the potential environmental pollution caused by the chemical injection method are the reasons that prevented the rapid development and marketability of these two mining methods, resulting in a low number of patents and slower progress.

In terms of the distribution of nodes, only China, the US, Japan, and Korea have distributed their respective patents in each of the technology themes represented by the clusters. In T4 and T7, the highest number of distributed patents indicating that China is at a competitive advantage in these two technology themes. In T5, the patents are mainly from China, the US, and Japan, which have similar competitive capabilities in this technology theme, and this is also the technology area in which Japan is most competitive. Russia's most competitive technology area is T6, even surpassing the US in second place.

3.3.2 Institution competitive landscape analysis

Unlike the predominantly competitive relationships between countries, it is common for institutions to have a mixture of cooperative and competitive relationships. The analysis of relationships between institutions is based on the method described in Section 2.2.3.

(1) Institution cooperation analysis

By using the calculation and visualisation methods of **Fig. 17** and deleting the isolated nodes to simplify the network, we obtain **Fig. 19**. This reveals the cooperative relationship among institutions.

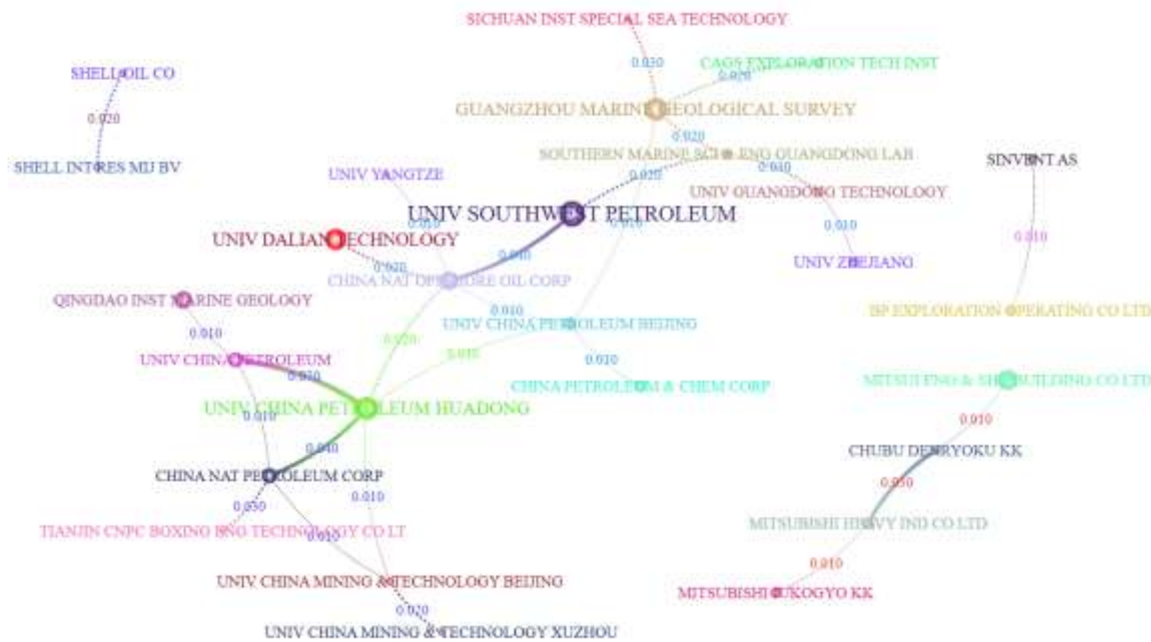

Fig. 19 Institution cooperation

In the top 50 institutions, we can see that only 24 institutions have cooperative relationships in **Fig. 19**. We can see that most of the values between institutions are below 0.04, which represents the intensity of cooperation that is generally low. Among them, there are four significant relationships: CHINA NAT OFFSHORE OIL CORP and UNIV SOUTHWEST PETROLEUM, UNIV CHINA PETROLEUM HUADONG and UNIV CHINA PETROLEUM, UNIV CHINA PETROLEUM HUADONG and CHINA NAT PETROLEUM CORP, MITSUBISHI HEAVY IND CO LTD and CHUBU DENRYOKU KK; and the values are 0.04, 0.07, 0.04 and 0.05, respectively.

Fig. 19 also shows that the cooperation between institutions is usually domestic and rarely transnational. Domestically, the cooperation network is mainly developed with three institutions as the center: UNIV CHINA PETROLEUM HUADONG, CHINA NAT OFFSHORE OIL CORP, and GUANGZHOU MARINE GEOLOGICAL SURNEY. Furthermore, enterprises are more likely to collaborate with others than universities and research institutes. For example, CHINA NAT OFFSHORE OIL CORP has cooperative relationships with UNIV SOUTHWEST PETROLEUM, UNIV CHINA PETROLEUM HUADONG, UNIV DALIAN TECHNOLOGY and so on as shown in **Fig. 19**. On the contrary, there is less cooperation between universities or research institutes.

(2) Institution competition Analysis

We set the threshold for the strength value of the correlation at 0.50 and rearranged the layout after removing the isolated nodes to obtain **Fig. 20**. This network shows the competitive relationship between institutions based on the co-occurrence of DMC.

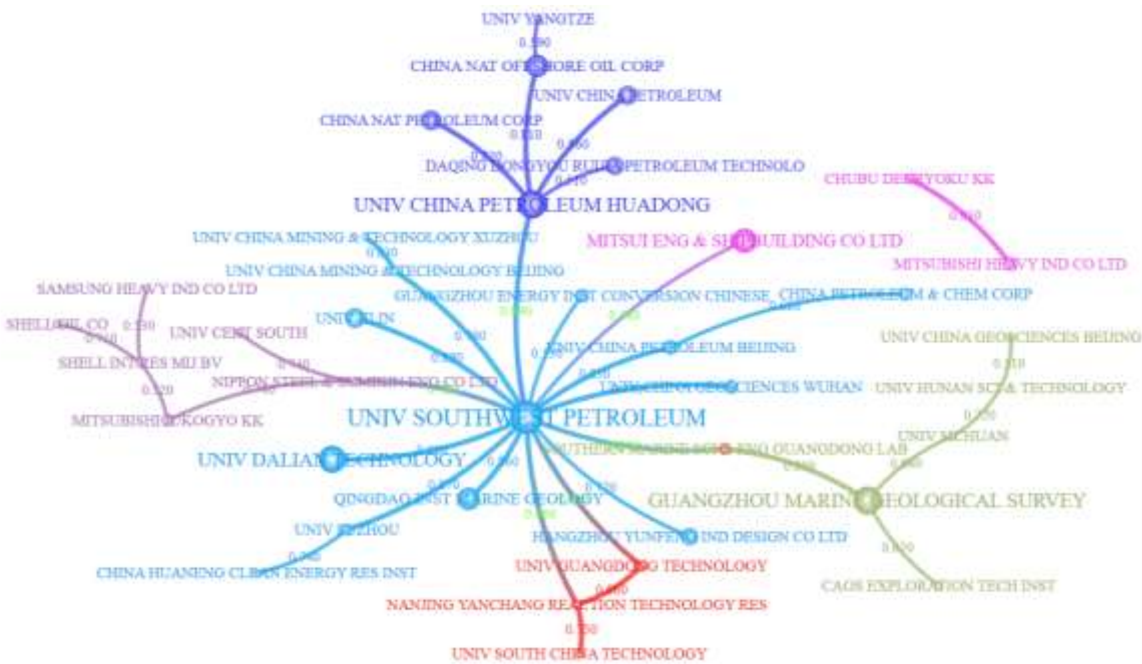

Fig. 20 Institution correlation

The detail DMCs of the top 10 institutions is shown in **Table 3**. We removed Q49-A, which was present in the main DMCs in each institution, and only retained the heterogeneous DMCs among institutions.

Table 3 Main DMCs for each institution

Institution Name	Main DMC					
UNIV SOUTHWEST PETROLEUM	Q49-A01, 7	H01-B03C3, 7	H01-B01, 6	H01-B03B3, 6	H01-D03, 5	H01-D08, 5
CHINA NAT OFFSHORE OIL CORP	H01-B01, 7	H01-D04, 7	H01-D08, 7	T01-J13, 6	T01-J09F, 4	H01-B05A, 4
UNIV CHINA PETROLEUM HUADONG	H01-B01, 6	H01-C03, 6	H01-D04, 5	H01-D12, 5	Q49-A01, 4	H01-C07, 4
GUANGZHOU MARINE GEOLOGICAL SURVEY	Q49-H, 7	Q49-A01, 5	H01-B03B3, 4	H01-D12, 3	S02-K01, 3	T01-J15X, 3
CHINA NAT PETROLEUM CORP	H01-B03B, 9	H01-B06, 8	H01-B01, 7	A12-W10A, 6	H01-B03B3, 6	S03-E13D, 5
UNIV DALIAN TECHNOLOGY	H01-D08, 4	H01-D12, 4	H01-B01, 3	H01-D04, 3	H01-D06C, 3	H01-D06, 3
MITSUI ENG & SHIPBUILDING CO LTD	E31-N05C, 4	H06-A, 3	J04-X, 3	E11-Q02, 3	D04-A01F1, 2	D04-A01C, 2
QINGDAO INST MARINE GEOLOGY	H01-B03D, 5	H01-C08, 5	H01-D12, 5	H01-D08, 4	H01-B03B3, 5	H01-B03C3, 4
CHINA PETROLEUM & CHEM CORP	H01-B03D, 6	H01-D06, 6	E12-B02, 4	E11-W, 4	S03-C01X, 4	A12-W10A, 4

UNIV JILIN	H01-B03C3, 4	H01-B03C1, 3	H01-B03D, 3	H01-C01, 3	H01-D08, 3	H01-B01, 3
UNIV CHINA PETROLEUM	A12-W10A, 3	H01-B03B, 2	H01-C03, 2	H01-D06C, 2	H01-D12, 2	S03-C01C1, 2
DAQING DONGYOU RUIJIA PETROLEUM TECHNOLO	A03-A00A, 6	A12-W10A, 6	E10-E04H1, 5	E10-E04L1, 5	E33-B, 5	A04-D05A, 4
HANGZHOU YUNFENG IND DESIGN CO LTD	P41-A05, 8	Q49-A01, 6	P41-A03, 5	Q49-B01A, 3		
BAKER HUGHES INC	H01-C03, 2	H01-C10, 2	H01-E, 2			
UNIV CHINA PETROLEUM BEIJING	H01-A, 2	H01-B03D, 2	Q49-A01, 2	S03-C01X, 2		

Using **Fig. 20** and **Table 3**, we selected three representative institutions as analysis subjects. One is UNIV SOUTHWEST PETROLUEM, which ranks first in the number of patent filings. The second is MITSUI ENG & SHIPBUILDING CO LTD, the only Japanese institution in the top ten, apart from those from China. The third is DAQING DONGYOU RUIJIA PETROLEUM TECHNOLO, which has more special main DMCs.

(1) UNIV SOUTHWEST PETROLUEM

Since UNIV SOUTHWEST PETROLUEM is the institution that has applied for the largest number of patents and has a significant relationship with many other institutions (**Fig. 20**), we show the part of the institutions that are associated with UNIV SOUTHWEST PETROLUEM separately in (**Fig. 21**).

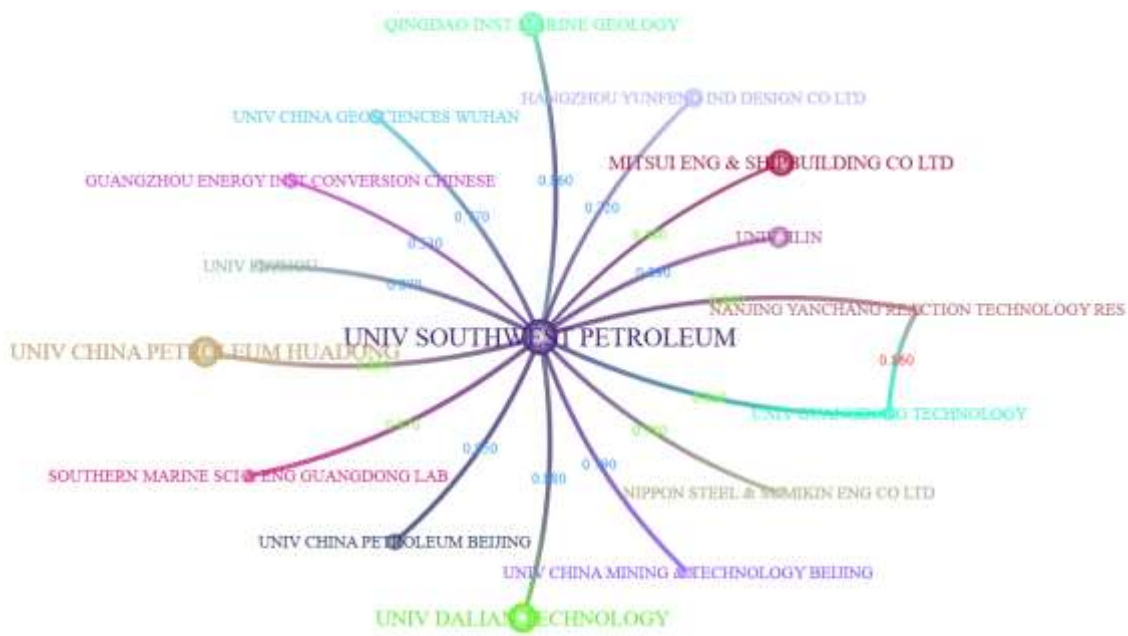

Fig. 21 USWP local correlation network

Comparing with **Fig. 19**, among the institutions in **Fig. 21**, only SOUTHERN MARINE SCI & ENG

GUANGDONG LAB and CHINA NAT OFFSHORE OIL CORP have a cooperative relationship with UNIV SOUTHWEST PETROLUEM, and the strength values reaches 0.02 and 0.04, respectively.

From **Fig. 21**, we can see that there are 12 institutions with correlation strength value of 0.70 or more with UNIV SOUTHWEST PETROLUEM. In order to further study which technology fields overlap between these institutions and UNIV SOUTHWEST PETROLUEM that caused the strong degree of correlation, we selected them and the top 20 DMCs to produce **Fig. 22**.

Fig. 22 Main technical distribution of relevant institutions

Vertically, we can see that H01-B01 (Marine Drilling structures and equipment), H01-D08 (Producing crude oil and natural gas - Thermal methods) and H01-B03D (Transmission/Generation of power, data, etc.) are all the relatively basic or widely used technologies, almost every institution in **Fig. 22** has patents related to them. UNIV SOUTHWEST PETROLUEM has a clear advantage in H01-B01, H01-B03B3, H01-B03C3, H01-D03 (Producing crude oil and natural gas - Pumps), H01-D08, and Q49-A01 (Extraction equipment), which are mainly the DMCs that closely related to the solid fluidised mining method (Tang *et al*.; Wang, G. *et al*.; Zhang, Y. *et al*.; Zhang, Z. *et al*.). Besides, it also has some patents related to thermal injection. For example, “A mining method and equipment of natural gas hydrate in shallow seabed”, change the solid-state existence conditions of NGH mainly by subsea heating method, and further decomposes the NGH in the mixture (Wang *et al*.).

Horizontally, though UNIV SOUTHWEST PETROLUEM has the largest number of patents among them, UNIV CHINA PETROLEUM HUADONG holds the most extensive technical coverage. UNIV CHINA PETROLEUM HUADONG, UNIV JILIN, and QINGDAO INST MARINE GEOLOGY have more technology overlap with UNIV SOUTHWEST PETROLUEM and no cooperation, which causes their correlation strength to reach 0.89, 0.89 and 0.86. In particular, QINGDAO INST MARINE GEOLOGY, which has many patents in the same technology area where UNIV SOUTHWEST PETROLUEM has applied for, indicates a significant competitive relationship between them. There are many technology areas in which they compete. Among these areas, it has obvious advantages in H01-B03B3, H01-B03C3, H01-D03, Q49-A01, while its patent layout is weaker in the technology areas of H01-C03, H01-C07, H01-

D12, etc. This indicates that strengths of UNIV SOUTHWEST PETROLUEM are mainly concentrated in the technologies related to solid fluidised mining method.

(2) MITSUI ENG & SHIPBUILDING CO LTD

MITSUI ENG & SHIPBUILDING CO LTD ranks seventh in the number of patent applications, however, the networks reveal that it has no cooperation with other institutions, and a slight correlation only with UNIV SOUTHWEST PETROLEUM. In **Table 3**, we can see that the main DMCs belonging to MITSUI ENG & SHIPBUILDING CO LTD are significantly different from those of other institutions, which is why they have no correlation with other institutions. Many of them are related to CO2 replacement method (E31-N05C: CO2), a mining method in which institutions in other countries have few relevant patents. Currently, the other two institutions that have applied for a larger number of patents related to this method are from Japan: MITSUBISHI HEAVY IND CO LTD and CHUBU DENRYOKU KK. As it can be seen from **Fig. 20**, there is a strong relationship between these two institutions. By lowering the threshold in this network, a correlation between MITSUI ENG & SHIPBUILDING CO LTD and MITSUBISHI HEAVY IND CO LTD with a strength value of 33 can be found.

Except for E31-N05C, we know that MITSUI ENG & SHIPBUILDING CO LTD are the leaders in the areas of manufacture, storage, and transportation of NGH. Such as J04-X (Other chemical methods), D04-A01C (Purification of water by freezing, crystallization), D04-A01F1 (Other filtration process), and E11-Q02 (Removal, effluent treatment–process, apparatus), which may relate to these areas. For example, there is a method and apparatus for further reducing storage and transportation costs by continuously dehydrating, cooling, and solidifying with high efficiency to produce gas hydrates containing a low proportion of water (Kimura *et al.*). However, there are very few institutions that have filed patents related to this technology.

(3) DAQING DONGYOU RUIJIA PETROLEUM TECHNOLO

Among Chinese institutions, DAQING DONGYOU RUIJIA PETROLEUM TECHNOLO has most special and rare DMCs: A03-A00A (Polysaccharides uses), A12-W10A (Drilling mud or fluid), E10-E04H1 (Diol), E10-E04L1 (Methanal, use). These are the technologies for drilling fluids with gas hydrate inhibitors, by injecting chemicals to facilitate the decomposition of NGH and conduct the exploitation. Except for A12-W10A, it has several main DMCs that are rare in other institutions in China, but appear frequently in institutions from the US. This illustrates that this company competes primarily with institutions in some other countries, rather than domestic institutions.

4 Conclusions, managemental implications and limitations

4.1 Conclusions

This study proposes a framework to monitor the developmental trend and competitive landscape of technologies in marine NGH via patent analysis. From the perspective of patentometrics, we conducted an overall layout of the temporal and quantitative trends, geographical distribution, patentee distribution and technology distribution of NGH related patent applications. Then, based on the subject terms, the evolutionary paths of NGH related technologies were analysed, which were used to determine technological development trends. Finally, we analysed the competition and cooperation landscape among countries and institutions in key technical fields.

Firstly, in terms of patents overview, the development of marine NGH has a long history and has shown significant growth in the last 20 years. With many countries placing increasing emphasis on the development and application of NGH-related technologies, with China, The US, and Japan having clear advantage in the number of related patents, and Australia, Brazil, Canada, Russia, and South Korea are also important patenting countries. China has a wide distribution of technology areas and comprehensive patent reserves. We have seen a surge in patent applications over the last decade and has quickly become the country with the largest number of patents in the world. Today, the developmental trends in marine NGH technologies are relatively concentrated, and the patent data owned by the main patentees showed the advantages of agglomeration. Nine of the top ten patentees are from China with one from Japan.

Secondly, in terms of the technical themes the patents, the current development of marine NGH technology is more oriented towards the fields of extraction technology and equipment, and the field of processing systems and technologies. The former mainly focuses on various mining methods and techniques, as well as tools and equipment used in the extraction process, while the latter focuses on data acquisition, transmission and control, etc. Of the five main mining methods for marine NGH, the CO2 replacement method has been a popular area of research due to its high environmental friendliness. However, due to the operational difficulties and inefficiencies in actual mining, this method has never been successfully applied to large-scale test mining. In contrast, in recent years, thermal injection and depressurisation methods have been commonly used in the test mining of marine NGH. R&D and patent applications on basic and mature mining methods are increasing. The chemical extraction method, due to the potential pollution of the marine ecosystem, the number of related patent applications is relatively small. The number of related patent applications in chemical extraction method is small due to the potential pollution of the marine ecosystem. The solid fluidised mining method has developed in recent years, with research being carried out mainly by Chinese institutions.

Thirdly, Today, in marine NGH-related technologies, the world's largest international cooperation network is mainly distributed in Europe and the United States, with the US as the center, Australia, EPO, etc. as the lead. Whereas national partnerships in Asia are mainly between China and Japan. Through the analysis and comparison based on DMC and subject terms respectively, we can see that extraction tools and equipment, drilling fluids, and thermal injection technology are the research hotspots in each country, and competition in these areas is relatively intense. In contrast, the competition in the field of chemical mining methods and CO2 replacement method are weaker and the number of related patents is smaller. But, these technologies are potential areas of competition in the future. There is a need to increase investment in these areas to improve R&D capabilities and opportunity for further research. In addition, the results of the clustering networks not only point to areas of technology that require greater investment in R&D, but also provide direction to countries in their search for possible partners. For areas where technology development is not yet mature, technological breakthroughs can be sought together by collaborating with countries with more advanced research facilities, where they have more mature technology development. By extensive collaboration between countries, it is possible for us to find technological innovations to further promote and improve the commercialisation of marine NGH extraction technologies.

Finally, as the institution with the highest number of patent applications, UNIV SOUTHWEST PETROLUEM is associated with numerous institutions. However, all institutions with strong ties to it are from China, and transnational relationships are rare. Similarly, most cooperative and correlation relationships held by institutions from other countries are with institutions in their own countries. Our analysis shows that the technical cooperation in marine NGH is limited and the technical barriers are high. Currently, in China, the majority of patentees are universities and research institutes, and the number of patent applications from enterprises is generally low, indicating that marine NGH-related technologies are still at the basic theoretical research stage and are still some distance away from maturity and commercialization. Technologies have undergone long term evolution due to the long period of research of Maine NGH in US and Japan. Because of this, the patentees in these countries are enterprises, demonstrating more advanced commercialization progress.

4.2 Managemental implications

Today, the R&D of marine NGH is changing from "experimental exploitation" to "productive exploitation", combining theory with market demand and applying it in actual mining processes will be the focus in the future. To utilities, the use of NGH as potential alternative energy development, government should pay great importance to its research and development at the industrial and market levels. Universities and research institutes should follow industrial dynamics, promote basic research for practical applications, and accelerate the transfer of scientific research results. Enterprises should strengthen cooperation among industry, universities, and research institutes, consolidate core technology reserves, strive to build their own intellectual property rights system, and stimulate independent innovation to improve competitive ability.

For the government and industry, it should pay attention to the following two aspects in guiding the commercialization process of NGH. Vertically, there should be a sustained focus on industry-academia-research cooperation among various types of institutions. Some Chinese institutions have already demonstrated mature partnerships, such as CHINA NAT PETROLEUM CORP and CHINA NAT OFFSHORE OIL CORP, and have cooperative relationships with a number of universities and research institutes, working with a wide range of partners and showing good cooperation Secondly, horizontal cooperation between institutions of the same type should be strengthened. During the analysis, it can be seen that the current level of horizontal cooperation among Chinese institutions is still low, whereas in both the US and Japan cooperation is mainly between enterprises. For China, cooperation among universities and research institutes needs to be further enhanced by extending the network of cooperation and increasing the number of partners. In terms of enterprises in NGH for technology areas with a high concentration of patent applications, competition should be reduced and R&D in other technologies should be accelerated. In contrast, for technology areas with fewer patent applications and weaker competition, consideration should be given to multi-party cooperation and collaborative innovation for developing advantageous areas.

4.3 Limitations

This study has several limitations. Firstly, although patents of marine NGH account for more than 90% of total NGH patents, one future work should investigate NGH patents in permafrosts to enrich the diversity of findings.

Secondly, despite technology being the core feature of patents, papers and standard reports are still research sources of multi-source data. Our future work will expand data sources to strengthen both the analysis on theory and application except for technological research in the NGH field.

Appendix

Table A1 Distribution of the top 15 DMCs of key technologies

Record	Description	Count
Q49-A	Mining and quarrying equipment	247
H01-B01	Marine Drilling structures and equipment	82
H01-D05	Marine production equipment for crude oil and natural gas	61
H01-D08	Producing crude oil and natural gas – Thermal methods	57
H01-B03D	Transmission/Generation of power, data etc.	56
Q49-H	Maintenance equipment; Equipment and methods for removing tools from mines, boreholes or wells	47
Q49-A01	Extraction equipment	44
H01-B03B3	Rotary drilling – Valves and control equipment	43
H01-D12	Testing, control operations and equipment, general	43
H01-D04	Producing crude oil and natural gas – Separators	38
H01-B03C3	Rotary drilling – Drill pipe	34
H01-D03	Producing crude oil and natural gas – Pumps	33
H01-C03	Fracturing; Fracking	22
H01-F01	Natural gas – Field treatment and processing	22
A12-W10A	Drilling mud or fluid	21
E31-N05C	CO2	21
H01-C01	Well completion, stimulating, and servicing – Casing and tubing	21

Table A2 Main subject terms in each cluster

Cluster	Main Subject Terms						
T1	gas hydrate deposit, 15	reaction kettle, 12	subterranean formation, 11	water storage tank, 10	water pump, 7	heat exchanger, 7	gas compression separator, 5
T2	liquid hydrocarbon, 4	hydrate slurry, 4	bottom portion, 4	gas hydrate agglomeration, 4	oil pipe, 3	hydrate decomposition, 3	liquid storage tank, 3
T3	hydrate layer, 17	carbon dioxide, 4	product storage, 4	methane gas suction line, 4	methane substitution storage tank, 3		
T4	lower end, 27	upper end, 21	lower part, 18	output shaft, 9	insulation oil, 8	drill rod, 6	hydrate layer, 5

T5	carbon dioxide, 33	global warming, 12	carbon dioxide hydrate, 7	energy consumption, 6	hydrate layer, 5	electric power generation, 5	sodium chloride, 4
T6	mining platform, 9	carbon dioxide, 6	internal pressure, 4	cement slurry, 4	sound wave, 4	pressure reduction method, 3	
T7	hydrate layer, 31	gas liquid separator, 12	gas pipeline, 11	natural gas hydrate exploit, 10	drill bit, 8	control valve, 7	gas hydrate decomposition, 5
T8	water pump, 14	gas hydrate inhibitor, 10	solid gas hydrate, 7	control system, 7	riser tube, 5	gas hydrate decomposition, 4	drill fluid, 4
T9	hydrate reservoir, 23	heat exchanger, 19	hot water, 11	temperature sensor, 4	sea water heat, 3	heat pump, 3	heat source, 3

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Ethics declarations

Ethical approval

The authors declare that no human participants and/or animals were involved in this work.

Consent to participate and publish

All authors confirmed that they provided a substantial contribution to the conception or design of the work; to the acquisition, analysis, or interpretation of data; to draft the work or revise it.

Competing interests

The authors declare no competing interests.

Author Contributions

Conceptualization, Zhenfeng Liu; Formal analysis & Methodology, Jian Feng; Project administration, Zhenfeng Liu; Resources, Pianran Lü; Writing – original draft, Pianran Lü; Writing – review & editing, Zhenfeng Liu & Lorna Uden.

Funding

This study was financially supported by Shanghai Science and Technology Program (Project No. 22692113300).

Acknowledgments

We are thankful to all those who have helped in carrying out the research.