Life Cycle Analysis of the Coalbed Methane Industry Based on Technology Paradigm and Data Analysis System Method

Zhiqian Mao¹, Lurong Fan²*, and Nizhu Pan³

¹Business School, City University of Hong Kong, Hong Kong 999077, People’s Republic of China
²Business School, Sichuan University, Chengdu 610065, People’s Republic of China
³Business School, The University of Melbourne, Melbourne VIC3010, Australia

Abstract. With the sharply increasing natural gas demand, coalbed methane (CBM), one of the main unconventional gas, significantly impacts the international energy supply. Driven by the global energy market demand, related technologies have been developed. However, previous studies of the CBM industry mostly focused on the description of a single technical field, lacking integrity and versatility, and unable to systematically describe the development of the technology track of the CBM industry. To summarize the life cycle of the technology development of the CBM industry, this paper proposes a new optimization methodology that combines the technology paradigm theory and data analysis system (DAS). Through data visualization, three technical paradigms are proposed: Competition, diffusion and transfer. Based on the visualization results, this paper discusses the challenges existing in the current CBM industry. It proposes corresponding policy recommendations so that the government can formulate appropriate and accurate subsidy incentive policies. Keywords: Coalbed mathane, Life cycle, Data analysis system, Technological paradigm, Policy.

1 Introduction

Nowadays, there is an increasing demand for energy and environmental protection, which lets the promotion and utilization of clean energy become a hot trend [1]. Natural gas, as a common clean energy, emits less pollution than other traditional fossil energy. In 2020, China’s natural gas production was 192.5 billion square meters and consumption was 324 billion square meters, resulting in a large gap between supply and demand [2]. According to the International Energy Agency, China’s natural gas consumption will reach 398 billion square meters by 2025 [3]. With the increase in demand, it is particularly important to supplement the gap. Natural gas is divided into conventional natural gas and unconventional natural gas, coalbed methane (CBM), as a kind of unconventional natural, is one of the best substitutes for natural gas [4]. Therefore, using CBM to alter natural gas appears to be a viable way.

In fact, many studies have been carried out to promote CBM utilization. In the initial period of CBM research, CBM is regarded as a kind of harmful gas, which has caused coal

*e-mail: fanlurong@scu.edu.cn

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mine gas explosion accidents. In this period, the research on CBM focuses on how to prevent its explosion in the mine [5]. Until the late 1970s, the research extended to evaluate the feasibility and economy of using CBM as energy [6]. Since then, in order to promote the development of the CBM industry, technology has made breakthroughs and reforms in exploration, drilling, fracturing, gas production and relevant research in these fields is being carried out simultaneously [7]. Driven by the global energy market’s demand, the technology related to continuously and efficiently producing CBM has developed [8].

The technology paradigm is widely used to solve management and decision-making problems, because it can identify the unsolved problems in the existing technology, obtain the industry technology life cycle, and thus clarify the development law of the industry and reveal the future technology trajectory [9]. In order to better promote the development of the CBM industry, it is necessary to comprehensively explore the technological trajectory of the CBM industry, which is the external form of expressing the constantly changing technological paradigm. Due to the lack of reviews of the CBM industry, it is unable to systematically describe the life cycle of the technology development of the CBM industry. In order to fill the gap in this kind of research, this paper combines a technological paradigm and data analysis approach to identify the life cycle of the CBM industry. Due to the large number and time span of related research on the CBM industry, it is difficult to acquire key technological trajectories by reviewing all related research. Therefore, this paper constructs a data analysis system (DAS) based on bibliometrics, and constructs a visual network by mining the key data of the paper. Through the visualization analysis, this paper reveals the three stages of the technological paradigm of the CBM industry: competition, diffusion and transfer, thus forming the S-shaped curve of the CBM industry. On this basis, explore the current challenges in the CBM industry, and discuss solutions to the existing challenges.

The remainder of this paper is structured as follows. Section 2 obtains the literature Atlas of the CBM industry through the technical paradigm and DAS, and obtains the technical track of CBM development. Section 3 analyzes the three stages of the development life cycle of the CBM production technology paradigm. Section 4 discusses the challenges and policy recommendations of the current CBM industry. Section 5 gives the conclusion and future research direction.

## 2 Method and Results

The use of data visualization technology needs to be based on the existing massive research data [10], and there have been thousands of bibliometric studies in the CBM research community. Therefore, base on literature mining and analysis, this paper explores the technical paradigm of CBM through the introduction of DAS. The visualization network graph with different label clusters is obtained through visualization technology. Then, through the theory of technological paradigm, the key path and trend of CBM development are revealed. This section will describe the visualization of the technology paradigm, the construction of DAS and the results of visualization analysis.

### 2.1 Visualization of Technology Paradigm and Construction of DAS

The paradigm is defined as a recognized model that a specific scientific community will follow when engaging in certain scientific activities [11]. Scientific development can be regarded as an inevitable process of change. In the pre-scientific stage of scientific development, due to the more research direction, it is impossible to form a unified paradigm. However, with the development of internal science, the key technology will be found to form
a paradigm. Driven by the demand of the industry, technology can be further developed and a new paradigm is formed in a specific stage [9]. The iteration of the paradigm is able to show the track of technology development, and provide direction for future development. In the CBM industry, there are many scientific documents on developing various technical aspects. Therefore, based on existing literature, this paper uses the method of bibliometrics to analyze the progress of critical technologies in the CBM industry.

Based on the text data extracted from the ScienceNet database, CiteSpace can conduct collinearity analysis by mining relevant literature of CBM and then show the direct relationship through image rendering technology [12]. Based on plenty of mapping functions, CiteSpace uses document visualization technology and keyword clustering algorithm to process the digitized documents, and displays the processed results in the form of images [13]. The analysis of visualization results will clarify the core technology and technology development trend of the CBM industry. DAS provides a comprehensive integration method, combined with CiteSpace software to clarify the keyword trend in Web of Science (WoS), and then through the visual image to analyze the literature.

This paper selects the bibliometric from the core collection database of WoS, and uses the search string (TS=CBM) to search the relevant literature from 1979 to 2021. After the search is completed, document types such as articles, conferences, patents, and reviews will be selected. After filtering out unnecessary research on CBM device design, 3820 related articles were downloaded and saved as the CiteSpace input file. The attached data records were composed of the author, title, abstract, keyword and reference. The DAS literature mining process, as shown in (figure 1), records the return and utilization of the paper data in detail. Then uses the Pathfinder method to handle the keyword as cluster nodes. In the data processing window of CiteSpace, select the cluster and obtain the research hot words about CBM. The results of the CBM industry literature keyword clustering are shown in figure 2.

In order to obtain the visualization results of CBM industry development from the collected data, sets the period from 1979 to 2021 as the time slice parameter, sets the number of years of each slice to 5, and conducts the dynamic analysis of its keywords [14]. figure 3 shows the analysis of the keyword. In the time-line view, the key technology time chart is generated for the clustering research hot words; And in the time-zone view, the knowledge map of CBM technology keywords clearly shows the update of research.

### 2.2 Results of Visualization Analysis

The related scientific frontier is calculated by the CiteSpace’s clustering algorithm which is based on the frequency rate of keywords. In the generated visualization map, when the centrality is greater than 0.1, the node will be automatically generated. The larger the centrality of the node, the more research the node keywords correspond to, the greater the impact, and the more obvious the node is in the knowledge network, and TF * IDF weighted algorithm is selected for clustering. In order to test the significance of clustering results, this paper proposes two indexes: observation Silhouette (S) and Modularity (Q). The S value represents the reliability of the overall clustering results, and Q represents the significance of the clustering results [15]. The clustering results show that s = 0.7765, q = 0.6898, which confirms the effectiveness of the visualization results.

Through the CiteSpaces keyword co-occurrence network, irregular regions are clustered, each region corresponds to a label, which represents different degrees of clustering. As shown in the “Cluster View” graph, keywords are grouped into 12 categories. Then using the distribution of the time axis view and time zone view, it is found that three clusters can clearly represent the evolution path of the whole related research, and further confirmed that three clusters (IDs = 1, 4, 10) represent three different stages, so as to show the development of the
technological paradigm of CBM industry and explore the development path of CBM. Among them, the cluster tag with ID = 1 is mainly related to the development of CBM. The related keywords are the development of natural gas, the birth of CBM in unconventional natural gas, the resource evaluation related to CBM and the development of CBM. This is related to the development of the energy revolution, from conventional natural gas to unconventional CBM exploitation. The purpose of these studies is to explore the availability of CBM resources and improve the safety, feasibility and effectiveness of CBM production. Cluster tags with ID = 4 are mainly related to carbon dioxide sequestration. The keywords are carbon capture and sequestration, carbon dioxide injection and CBM stimulation (ECBM). This is because after finding new energy, clean energy is required to reduce CO2 emissions. Therefore, it promotes the innovation of development technology of the CBM industry, and requires the storage of CO2 during the development of resources, so as to reduce pollution and promote the development of green energy. The cluster marker with ID = 10 is related to the detection of CBM by nuclear magnetic resonance (NMR). Through more accurate NMR testing, it is found that there are great differences in coal seam properties in different areas, and the different coal seam structure has a great impact on the selection of mining technology, min-

![Diagram](https://example.com/diagram.png)

**Figure 1.** DAS literature mining process
3 CBM Industry Development Technological Life Cycle Analysis

As a key driving force for the development of the energy industry, technological innovation is regarded as an inevitable iterative process, which is used to meet new demands in the market. When new technology enters the market, the speed of adaption seems to be particularly slow, because compared with the old technologies, the high cost and low efficiency expose its immature. However, as time goes on, new technology in the field of continuous development, its application has become increasingly widespread which makes it gradually occupy the market. But when the technology develops steadily, another new technology will enter the market and compete with it. In other words, in the life cycle of technology, the paradigm of
technology always follows the S-shaped curve and it shows the stage characteristics [16], and the theory of CBM exploitation is shown in figure 3. DAS shows that there are three stages of the life cycle of the CBM industry, which are able to reveal the research hotspot direction and the technological evolution (figure 4): the competitive stage of coalbed natural gas, which is characterized by the exploration of new technological solutions; The diffusion stage of coalbed dioxide sequestration is characterized by industrial technology innovation under new demand of market; In the transfer stage of nuclear magnetic resonance, the demand of emerging markets for this technology tends to be saturated. Driven by energy demand in the international market and competition in the energy industry, accurate and efficient exploitation of CBM, such as nuclear magnetic resonance, is regarded as an advanced and practical CBM exploration technology. In the meanwhile, the development of the CBM industry life cycle is closely related to policies as the government attaches great importance to the development of CBM industrialization. Therefore, governments of different countries have formulated appropriate laws and policies in their CBM industry to support the development of CBM in different life cycle periods (figure 5).

3.1 Competitive Stage—Coalbed Natural Gas

CBM is an important energy resource that is capable of altering natural gas. In 1920, Rice proposed the idea of removing methane from coal seams by vertical drilling before coal mining. In the 1930s, small-scale commercial exploitation appeared in the Appalachian basin of the United States. In the early 1950s, small-scale production of CBM began in the San Juan basin of Colorado and New Mexico. Then, in 1969, the U.S. Bureau of Mines drilled the first goaf gas drainage well. In 1970, the concept of exploiting CBM as a potential and effective alternative energy source was formed in the United States. The U.S. Bureau of Mines started to publicize the incentive scheme of pumping CBM by vertical degassing wells in most major coal-bearing basins.

Because of the recognition of the governments, the technology of CBM began to be studied. Initially, the researchers evaluated the CBM resources and pointed out the advantages of CBM by estimating the CBM content and analyzing the feasibility [17]. After that, the market gradually realized the scale and importance of CBM resources. Because of the recognition of the market, the complete technological process of CBM exploration has been studied [18]. Under the background of American research results, other countries such as Australia had also started the research of CBM and the world’s view on CBM had changed: from a haz-
Figure 5. Government policies corresponding to CBM life cycle

ardous resource to available energy. At this time, CBM entered the competitive stage. At this stage, the CBM industry technology had been explored but also met with challenges, which drove the technology to seek new changes.

3.2 Diffusion Stage– Coalbed Dioxide Sequestration

With the recognition of global environmental problems, governments have actively adopted various measures to promote environmental conservation, green development and sustainable development. Therefore, how to store CO2 has become a hot technology in the energy industry, and the energy that can store CO2 will be able to obtain greater market demand. In order to adapt new demand of the market, a large number of studies that focus on carbon capture and storage technologies (CCS) of the CBM industry have been pushed to the hotspot.

The enhanced natural gas recovery (EGR) technology through CO2 injection and the replacement of CH4 by CO2 technology of CBM have emerged one after another [19]. CCS research in the CBM industry not only focuses on how to store the carbon dioxide in coal, but also focuses on how to remove the methane from coal seams. In other words, use carbon dioxide to replace methane in the coal seam (figure 6). This enhanced coalbed methane (ECBM) technology not only improves the methane recovery rate, but also improves the profitability of operators.

The requirement for CO2 emission in the world urges the market to find a way to store CO2, which promotes the technological innovation of the CBM industry. The emergence of ECBM technology made the CBM industry enter the diffusion stage. At this time, the CBM industry had shown its advantages in the energy competition, the key technologies had been broken through, and the industry gradually became mature.

3.3 Shift Stage– Nuclear Magnetic Resonance

With the development of the CBM industry, enterprises find that under different geological environment conditions, CBM mining will have different efficiency, output, cost and technical requirements. In the meanwhile, the development of differentiated CBM technology has
Figure 6. CH4 replacement by CO2 injection (reprinted by Deep coalbed methane in Alberta, Canada: A fuel resource with the potential of zero greenhouse gas emissions [6])

Figure 7. Industrial process of CBM

become a new trend. In order to better carry out the exploitation of CBM, the whole industrial process has been systematically improved (figure 7), and the early exploration process has been gradually emphasized.

Nuclear magnetic resonance (NMR) was independently discovered by Purcell of Harvard University and Bloch of Stanford University in 1946. As a new imaging method, NMR has the specific characteristics of noninvasive and noninvasive to the detected object, so it can be used as the core technology to obtain the unconventional reservoir rock physical properties and fluid characteristics, and has gradually been widely used in coal seam exploration [20]. With a better exploration prediction model, the development of CBM tends to regional
differentiation, which means that CBM has entered the shift stage. At this stage, different technologies are used for CBM mining in different geological environments. Through accurate exploration, the differentiated exploitation plan of CBM under different terrain can be formulated smoothly.

4 Discussion

Based on the life cycle theory, with the development of technology, China’s CBM industry has now entered the shift stage. CBM operational feasibility and economic efficiency have become key indicators of core competitiveness. However, despite precise exploration, various challenges still exist in this stage. At the same time, energy policy is related to a country’s strategy, and the government needs to deal with energy development issues according to its own national conditions and stimulation targets. Therefore, this paper will discuss the challenges of CBM in terms of cost, technology and burial depth, and then discuss policy recommendations based on these three core challenges.

4.1 Challenges to CBM Industry Core Competitiveness

Compared with other traditional petroleum resources, the biggest challenge facing the CBM industry is cost. Due to the high cost of CBM enterprises and the lack of effective subsidy and stimulus policies, the development of the CBM industry is limited, unable to expand the source of the supply side. Due to the limitation of cost, the well selection can not reach the optimal level in the development process. In the meanwhile, due to the lack of CBM infrastructure in China, CBM production is out of touch with downstream consumption. Faced with huge infrastructure costs, the development of CBM is limited and resources cannot be used effectively.

The second challenge facing the CBM industry is the development of differentiated technology. Most of the previous technologies were specially designed for CBM exploitation in foreign countries, such as America, which has a better geological environment than China. Therefore, it is incorrect to directly copy them under the complex geological condition background in China. Even in China, there are obvious differences in the geological conditions of CBM between different regions, partial CBM mining technologies can not be applied in the harsh geological environment.

The third challenge facing the CBM industry is the difference in burial depth. The difference in the buried depth of multiple CBM production points will lead to the difference in coal seam permeability and gas content. With the increase of buried depth, the gas content of coal seam decreases [21]. Due to the low gas content in high buried depth areas, the marginal profit of mining is reduced [22]. In the meanwhile, the geological environment of CBM in China is special, and a large number of CBM resources are located in the high buried depth area [23]. In this situation, it is very difficult to develop resources efficiently, which restricts the rapid development of the CBM industry.

4.2 Policy Recommendations

In order to stimulate the development of the industry, this paper proposes to design a proportional ladder incentive policy. By calculating the output of each enterprise, three echelons are formulated according to the ranking. The first echelon company with the largest proportion of production will receive additional rewards in addition to the normal proportional subsidies; The second echelon company with the larger proportion will be given normal proportional
subsidies; And the third echelon company with the smaller proportion will be encouraged to carry out merger and reorganization.

In order to meet the technology needs of China’s CBM industry, it is necessary to subsidize technology differentiation innovation on the basis of the original single subsidy policy. Therefore, this paper proposes a technology subsidy policy to provide subsidies for qualified enterprises based on technical parameters. If the gas production efficiency per unit area is improved by updating the technology, the improved efficiency will be subsidized according to the regulations. And if the methane is replaced by carbon dioxide absorption by using advanced technology, the subsidy will be calculated by additional carbon dioxide absorption capacity.

In addition, to avoid the waste of resources and encourage the mining of CBM at high burial depths, this paper suggests that the policy of encouraging mining in high burial depth areas should be formulated according to different burial depth areas. The buried depth can be divided into three categories: below 800m, 800-2000m and above 2000m. Medium burial depth subsidy is set in the area of 800-2000 meters, and high burial depth subsidy and supporting technology subsidy are set in the area of more than 2000 meters.

5 Conclusions and Future Research

To systematically describe the development of the technology track of the CBM industry, this study proposes an innovative approach to exploring the development trajectory and trend of the CBM industry by combining the theory of technological paradigm with literature mining. By using a new DAS system, the CBM documents are mined. By using the visualization, three stages of the CBM development technology paradigm are defined: CBM exploitation technology in the competitive stage, coalbed dioxide sequestration in the diffusion stage and nuclear magnetic resonance in the transfer stage.

Based on the results of visualization, this paper introduces the technology life cycle to reflect the changes in the hot technology research direction and key technology revolution of the CBM industry. Through the analysis of the CBM life cycle, discuss the current challenges in the CBM industry, and then put forward targeted policy recommendations so that the government can formulate appropriate laws and policies to support the development of CBM in different periods. Taking CBM as the research object, the research idea of this study is also of great significance for understanding the process of clean energy technology development and market construction.

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