A dynamic forward-citation full path model for technology monitoring: An empirical study from shale gas industry

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HIGHLIGHTS

• A dynamic model is investigated to monitor the key technical development paths.
• The status quo of technical innovation of shale gas are quantitatively analyzed.
• Five potential hotspots are identified using topic modeling.
• A visualization of technology clusters was carried out by text mining.
• Simulation, deep fracturing and water treatment are supposed to have good prospect.

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ABSTRACT

The utilization of shale gas has become one of the important options to transit into low-carbon economy in the world and its vigorous development relies on successful technology revolution to a great extent. Based on patent data, this paper analyzes the development trends and the status quo of technical innovation of shale gas quantitatively by means of patent maps. A new dynamic model named Forward-Citation Full Path (FCFP) is investigated to identify the key development paths in technology clusters and monitor potential breakthrough technologies on those key paths. Then we employ topic modeling and text mining for patent abstracts to explore the potential promising topics with high innovation activeness in aid of providing specific references for development and foresight of the shale gas technology. The results show that: (1) The patent center of shale gas has been transferring from North American to the Asia-Pacific region and the technological innovation is mainly driven by preferential tax policy and loose environmental regimes. (2) Current hotspots of shale gas technology are production technique including stimulation treatments, environmental protection technology of fracturing fluid and geological prospecting technology. (3) There are five potential topics with high innovation activeness identified by topic modeling and text mining which are synthetic carbon oxide, hydraulic fracturing, fracturing propping agents, horizontal well, and technologies of reservoir exploration and modeling. (4) By means of visualization of technology clusters, it is found that promising technologies are refined simulation technology for shale gas exploration, multi-interval fracturing techniques in horizontal wells with deep pay zones, water treatment and environmental protection technology in shale gas production. (5) The suggested dynamic FCFP model can effectively identify the key development paths and monitor potential breakthrough technology of shale gas.

1. Introduction

Shale gas provides the nations with a powerful way forward to a lower emission future than traditional fossil fuels and will play an important role in the world energy prospect. The United States has successfully realized the commercial extraction of shale gas and thus effectively improved the energy supply structure, which is attributable to national strategic foresight and considerable development of breakthrough technology, like horizontal drilling and hydraulic fracturing [1]. In the wake of technology advance and cost reduction, it is estimated that the shale gas will account for 30% of the world natural gas output by 2040 [2]. Resource-holding countries except the United...
States, like China and Canada, are still in the initial stage of development [3]. These countries have successfully developed advanced technologies of shale gas suitable for own geological features and promulgated a series of policies to facilitate industrial innovative in order to satisfy the gradually increasing energy demand and reduce carbon emission. China, which is believed to have the largest reserves of shale gas in the world [4], also takes the shale gas as the key research project in energy sector during the 13th Five-Year Plan period.

Based on the status quo of technology, technical monitoring can be adopted to identify the development paths for innovation and foresee the technological development prospect. In order that the countries in the primary period of development have well-grounded policies in technology promotion of shale gas and can draw up efficient and pragmatic national foresight, it is necessary to establish one unified framework to analyze the development status quo of shale gas technology and identify the key development paths of various technology clusters in complicated patent networks of shale gas. Further, it can realize the technical monitoring of potential breakthrough technologies on the key paths and forecast the potential development fields of shale gas so as to provide solid foundation and correct direction for countries in long-term development.

Therefore, this article quantitatively analyzes the development trends and summaries the status quo of technical innovation of shale gas in combination with patent maps. A dynamic algorithm named Forward-Citation Full Path is proposed for complicated patent citation networks to identify the key technology development paths within each technology cluster of shale gas with a view to monitoring potential breakthrough technologies. And topic modeling method is adopted for patent abstracts to find out the potential topics with higher innovation activeness. Besides, we employ semantic mining means in combination with ThemeScape patent map\(^1\) to visualize topic distribution of all technology clusters and foresee potential development prospects of shale gas technology. And we aim at addressing the following questions:

(1) What kinds of laws do the technology innovation activity of shale gas present? And what is the status quo of the key technologies in this industry?
(2) Can the proposed algorithm effectively identify the key development paths for each technology cluster for the sake of monitoring the potential breakthrough technologies?
(3) What are the potential technology topics of shale gas with high innovation activeness and possible technology fields in future?

The remaining structures of this paper are as follows: Section 2 reviews relevant existing literatures; Section 3 describes the data sources and methodology; Section 4 discusses the empirical results; Section 5 summarizes the main conclusions and then puts forward some policy implications.

2. Literature review

The existing studies suggest technical revolution of energy can effectively promote the industrial development, and that key low-carbon technologies can facilitate the cleaning transition of energy-intensive sectors by means of enhancing the industrial potentials of energy-saving and emission mitigation [5–7]. Breakthroughs in two advanced technologies, namely horizontal drilling and hydraulic fracturing, have contributed to cost advantages of shale gas extraction and feasible large-scale commercial markets. In the long term, shale gas is supposed to be a clean alternative of conventional oil and gas resources with the challenges of climate change and growing energy demand [8–9]. There are three main uncertainties that will affect the future development of shale gas, that is reserve availability, environmental regulation and technology advance [10]. The first two factors will affect the future ability and impetus of shale gas production. While technical progress will be mirrored in the form of competitive price in the market [11] and accelerate commercialization of shale gas all over the world. Thus the uncertainty of technology development has become one of the most important obstacles that hinder the exploitation and utilization of shale gas in many resource countries [12]. The success of shale gas revolution in the US has attracted more attention from many scholars who make creative explorations on the industry development and social-economic benefits in this field [3,13–15]. According to research perspective, previous studies of technical development of shale gas can be divided into two following categories: (1) The interactions between the technical development and external environment, including both human and natural circumstances. (2) Assessments of techno-economics and future prospects for technology development.

The first perspective discusses the influence of environmental impact, public acceptance, and corresponding policies on technologies during the development period of shale gas [15–16]. For example, Vengosh et al. [17] reviewed four potential risks of emerging hydraulic fracturing to shallow groundwater, underground water, soil surface and water shortage based on case survey. Nicot and Scanlon [18] predicted water consumption for shale gas extraction on the basis of historical data and they believed that alkaline water will replace the fresh water to improve the industrial competitiveness of shale gas. Rahm [19] introduced the disputes brought by horizontal well and hydraulic fracturing technology and relevant regulations in Texas. Stanford and Azapagic [20] took full life cycle into consideration when evaluating the environmental impact of shale gas used for power generation for the first time. However, such studies focusing on the environmental friendliness of technologies usually analyze the resource-owner regions where commercial extraction of shale gas has been already realized, which can only play a guiding role for other post-developing countries in macroscopic perspective while developing technologies of shale gas and formulating relevant environmental regulations. It is rare to identify the development paths and directions of the technologies of shale gas and thus it is impossible to disclose more detailed information of technologies for relevant nations or enterprises.

The second category focuses more on techno-economic appraisal and evaluations on developing prospects of advanced techniques in shale-gas industry. For example, Gracceva and Zeniewski [21] calculated with TIMES model and found out that technical cost and the area of gas reservoir are the main factors affecting the development of shale gas in the future. Hu and Xu [22] hold that the main challenges for shale gas are lack of advanced technology and water resource in China and new opportunities can be ushered in by introducing foreign investors. Damrongchai and Tegart [23] investigated the development of fuel technologies in Asia-pacific region with scenario analysis and technology roadmap method and the results showed that the shale gas and shale oil would play an important role. Wei et al. [24] summarized technology development trends and key technologies for upstream of petroleum and natural gas industry in China. Lee and Sohn [25] compared the patentees and International Patent Classification (IPC) codes of shale-gas related technologies between China and the United States in a nutshell. It can be inferred that most commonly used methods are mainly qualitative like expert panel and scenario analysis whose results rely on the knowledge reserves of the candidates resulting in the lack of objectivity. Moreover, it is difficult to collect effective practical production data and thus impossible to directly identify the technology change direction [26], not to mention the breakthrough technology. Patent data is being an effective research tool for the analysis of technology development [27] and R&D investment in innovation due to its detailed technical information [28–30]. Technology monitoring is an important means to observe and analyze technology development in certain period of time [31–32], which can availably discern the

\(^1\) ThemeScape patent map, which is available in Thomson Innovation platform, is a visualization tool to describe the distribution of patent technology themes.
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