Patent-Based Technology Entropy Analysis Method and Its Application in Emerging Technology Monitoring: A Case Study of Carbon Capture Technology (Postprint)

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Abstract

【Purpose】Based on the characteristics of technological systems, this study proposes a technical entropy analysis method. Through patent literature data, it dynamically and effectively monitors the development and evolution of emerging technologies, thereby validating the effectiveness of the technical entropy analysis method.

【Method】A multi-dimensional technical entropy patent model is constructed within a patent-based technological system. Using carbon capture technology as a case study, technical monitoring and evaluation analysis are conducted from both macro and micro perspectives.

【Results】The results confirm the validity of the technical entropy analysis method. China' s carbon capture technology has undergone stages of technological germination, low-speed development, and high-speed leap. Although not yet mature, it has entered a crucial development stage. Technology R&D is primarily led by universities, with research mainly concentrated on absorption and adsorption materials.

【Limitations】The selection of sample data requires improvement, as interfering data exists.

【Conclusion】The technical entropy method is a scientifically effective analytical approach for examining evolution trends in technology fields from a technological systems perspective, providing a feasible analytical tool for issues related to technology evolution, technology evaluation, technology foresight, and associated technology management problems.

Full Text

A Patent-Based Technology Entropy Analysis Method and Its Application in Emerging Technology Monitoring: A Case Study of Carbon Capture Technology

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Abstract

[**Objective**] This paper proposes a technology entropy analysis method based on the characteristics of technological systems to dynamically and effectively monitor the evolution of emerging technologies through patent literature data, thereby validating the effectiveness of the technology entropy approach. [**Methods**] We constructed a multi-dimensional technology entropy patent model within a patent-based technological system and conducted monitoring and evaluation analyses of carbon capture technology from both macro and micro perspectives. [**Results**] The validity of the technology entropy analysis method was confirmed. China' s carbon capture technology has experienced stages of technological germination, low-speed development, and high-speed leap, and although not yet mature, has entered a crucial development phase. Research and development are primarily conducted by universities, focusing mainly on absorption and adsorption materials. [**Limitations**] The sample data selection requires improvement, as interfering data are present. [**Conclusions**] The technology entropy method represents a scientifically effective analytical approach for examining technology domain evolution from a technological system perspective, providing a feasible analytical tool for issues related to technology evolution, evaluation, foresight, and associated technology management concerns.

Keywords: Technology Entropy; Patent Model; Technology Monitoring; Carbon Capture

1. Introduction

Technology monitoring has become a critical means of tracking technological evolution and obtaining competitive technical intelligence. Generally based on scientific and technical information and data analysis, it employs cutting-edge information science techniques such as data mining, information extraction, knowledge discovery, and data visualization to dynamically monitor, analyze, and evaluate scientific and technological activities. Real-time dynamic tracking of emerging technologies through technology monitoring not only holds significant practical value for enterprises in formulating technology development strategies and patent layouts, but also provides important guidance for national, provincial, and regional science and technology development planning and for enhancing innovation capacity and core competitiveness.

Currently, analyzing technology evolution through patents using information visualization and data mining techniques represents an important approach in technology monitoring research and application. Additionally, some studies identify and monitor emerging technology evolution through patent indicators and mathematical models. However, existing research rarely monitors and analyzes technology development from the perspective of technological systems and their characteristics. As a crucial parameter 表征系统无序程度, entropy has been exploratorily applied across major scientific fields since its inception, leading to generalized entropy theories such as statistical entropy, information entropy, maximum information entropy, black hole entropy, management entropy, and economic entropy in natural and social systems. Due to the consistency between technological systems' characteristics—such as synergy, self-organization, and mutation—and other systems to which entropy theory applies, entropy theory is equally applicable to technological systems. This paper proposes the concept of technology entropy and its related criteria from a technological system perspective, presents a technology entropy analysis method based on patent literature data, and constructs one-dimensional and two-dimensional patent models. Using carbon capture technology as a case study, we analyze patent literature information downloaded from the State Intellectual Property Office to monitor and evaluate the overall development of China' s carbon capture technology, providing an objective and effective technical means and method for technology monitoring research and offering predictive suggestions for comprehensively advancing the industrialization of carbon capture technology in China.

2. Patent-Based Technology Entropy Analysis Method

Technological systems are contained within social systems and are influenced by both external factors and their own inherent attributes. From creation, development, and maturity to decline and eventual extinction, technological systems exhibit different states at various stages, with the driving force behind these changes being the unified manifestation of order and disorder among internal system elements. Building upon the definition of thermodynamic entropy and according to the relevant attributes of technological systems, this study proposes the concept of "technology entropy" to describe and characterize the degree of disorder in internal relationships within a specific technological system at a particular time. Its function is to reflect the evolution trends or maturity levels of technological systems to address issues related to technology evolution, monitoring, and evaluation.

Based on the thermodynamic entropy formula, this study defines technology entropy calculation as follows:

$$dS = \frac{dQ}{T}$$

where dS is defined as the technology entropy increment, dQ is the energy received by the technological system, and T is the research intensity for that technology. When $dS < 0$ (negative entropy increase), the technological system tends toward orderly growth; when $dS = 0$, the technological system reaches relative equilibrium, presenting a mature state; when $dS > 0$ (positive entropy increase), the technological system tends toward chaos and begins to decline.

This study establishes two criteria for the existence of technology entropy. The first is the entropy increment dS itself, which consists of two parts: one part is the entropy increment deS generated by energy exchange between the system and its environment, which can be positive or negative; the other part is the entropy increment generated within the system, i.e., entropy production diS, which is always positive. In summary, the technology entropy increment dS is expressed as:

$$dS = deS + diS$$

During the technology growth stage, since the input of external negative entropy flow dominates and internal entropy production is relatively small, we have $|deS| > diS$. Moreover, because $deS < 0$, $dS < 0$, meaning the technological system evolves in an orderly direction. When the technological system evolves to a certain extent, internal entropy production shows an upward trend while negative entropy flow shows a downward trend, eventually reaching equilibrium. The period during which this state is maintained represents the mature stage of the technological system, where $|deS| = diS$. In the technology decline stage, both positive entropy flow from the external environment and internal entropy production drive system chaos, causing entropy values to increase continuously, i.e., $deS > 0$ and $dS > 0$.

The second criterion for technology entropy is the technology entropy increment trend value h in the calculation formula $h = -\frac{dS \cdot T}{dQ}$. During the growth stage, the technological system evolves in an orderly direction with $dS < 0$, thus $h > 1$. In the mature stage, the technological system reaches a non-stable equilibrium state with $dS = 0$ and $h = 1$. In the decline stage, positive entropy flow breaks the mature equilibrium, making the technological system increasingly disordered with $dS > 0$ and $0 < h < 1$.

Technology entropy analysis is a method for analyzing technology lifecycle evolution based on the degree of internal chaos within a technological system from a systemic perspective. Its core idea lies in utilizing the entropy laws within technological systems to solve the systems' own problems. Therefore, its greatest advantage is "tailor-making" specific analytical methods for technological systems according to their particular problems. Technology entropy analysis reveals the development status of technological systems during technology evolution, reflecting not only macro-level technology development status but also micro-level details of technological changes, thereby objectively and effectively revealing issues such as technological weaknesses and obstacles in technology development status to provide references for technology forecasting. Consequently, employing technology entropy analysis to construct multi-dimensional technology entropy patent models enables technology monitoring and evaluation from macro to micro levels.

3. Construction of Multi-Dimensional Patent Models for Technology Entropy Method

Patents are effective carriers of technology, and the evolution of patent systems reveals the evolution of the technological systems they carry. Therefore, to validate the effectiveness of the technology entropy method in technology monitoring analysis, this study constructs a patent quantity model for technology entropy analysis based on relevant patent parameters. According to the technology entropy calculation formula and its existence criteria:

$$dS = deS + diS$$

where dS is the total entropy change of the system; deS is the entropy increment caused by interaction between the system and its environment, i.e., entropy flow, which can be positive or negative; and diS is the entropy increment generated by irreversible factors within the system, i.e., entropy production, which is always positive.

For research convenience, the following assumptions are proposed:
(1) All external factors act on the technological system through patents, i.e., a mapping relationship exists, making patents the sole pathway for technology exchange between the system and its environment under ideal conditions.
(2) Patents automatically exit the technological system in the form of entropy production if and only when they expire.
(3) Patents from different sources and of different types have different contribution rates to the technological system, and these contribution rates are measurable.
(4) Patent application volume can serve as a measure of research intensity.

Based on these assumptions, the order parameters for a certain technological system can be identified as: the application volume of the first type of patent dN_1 and publication volume dn_1 within a certain time range; the application volume of the second type of patent dN_2 and publication volume dn_2; ···; the application volume of the i-th type of patent dNi and publication volume dni. Patents can be classified by source or type.

Therefore, this study provides the following expression for deS based on patent indicators:

$$deS = \sum_i \frac{\alpha_i \cdot dn_{i-0}}{T_0} - \sum_i \frac{\beta_i \cdot dN_{i-0}}{T_0}$$

where deS_A is the entropy introduced into the system by authorized patents. Since it makes the system more "ordered" and has a positive impact, this portion of entropy is negative entropy with negative values. deS_B is the entropy change caused by unpublished patents in the system. These patents enter the technological system upon application but quickly exit, overall increasing the system' s disorder, and thus should be positive in value. Comparing the two, when the negative entropy introduced by authorized patents exceeds the entropy increase caused by unpublished patents, the entropy flow overall manifests as entropy reduction and the system tends toward order. When the negative entropy introduced by authorized patents is less than the entropy increase caused by unpublished patents, the entropy flow overall manifests as entropy increase and the system tends toward chaos. When they are equal, the entropy flow' s effect on the system is zero.

Defining the application and publication volumes of various patents within a unit statistical time as $dN_{1-0}, dN_{2-0}, ..., dNi-0$ and $dn_{1-0}, dn_{2-0}, ..., dni-0$, respectively, and letting T_0 represent the research intensity of a certain technology source in the base year:

$$T_0 = 1 + \sum_i x_i \cdot dn_{i-0}$$

where $x_1, x_2, ..., x_i$ are the intensity coefficients of various patents. This paper defines the T_0 value as 1 when all inputs $dn_{1-0}, dn_{2-0}, ..., dni-0$ are 0, making T_0 always a real number not less than 1. According to the entropy definition $dS = \frac{dQ}{T}$, we have:

$$deS = \sum_i \frac{\alpha_i \cdot dn_{i-0}}{T_0} - \sum_i \frac{\beta_i \cdot dN_{i-0}}{T_0}$$

where $\alpha_1, \alpha_2, ..., \alpha_i$ are the contribution rates of corresponding patent types to technology development in the base year, serving as weight coefficients. Patent types with generally higher levels contribute more to technology development and have larger α values, and vice versa.

Similarly, we can calculate:

$$diS = \sum_i \frac{\gamma_i \cdot dN_{i-\tau}}{T_0}$$

where $t_1, t_2, ..., t_i$ are the validity periods of corresponding patent types. $\varepsilon_1, \varepsilon_2, ..., \varepsilon_i$ are the average authorization rates of corresponding patent types, and $\tau_1, \tau_2, ..., \tau_i$ are the average application cycles of corresponding patent types. $dN_{1-\tau}, dN_{2-\tau}, ..., dNi-\tau$ are the application volumes of corresponding patent types in the $\tau_1, \tau_2, ..., \tau_i$ years before the base year. This is because there is a review cycle from patent application and acceptance to authorization. Patents can be considered to have entered the technological system from the date of acceptance. After review, unauthorized patents exit the system, while patents exiting in the base year should have been applied for before the average review cycle. Therefore, using the base year' s application volume for measurement is unreasonable. This approach not only improves the accuracy of patent measurement but also strengthens the logical connection between adjacent time nodes, thereby enhancing the overall integrity of the research.

In addition to entropy flow interaction with the external environment, the system also generates entropy production due to its irreversible factors. Calculation methods for entropy production are not uniform under different conditions, but the basic idea is to calculate irreversible losses within the system. Specifically, in patent-based technological systems, causes of entropy production can be simplified to patent expiration. On the one hand, expired patents still belong to the original technological system and exert influence internally, and the patent "expiration" process is highly irreversible. On the other hand, patent expiration is fundamentally different from patent non-authorization: the former has fully become a system component and played a substantive role during its validity period, while the latter only enters and exits the system as entropy flow without playing a substantive internal role. Therefore, only the former is the driving potential for system entropy production. Based on the above analysis and research assumptions, the entropy production calculation method for patent-based technological systems is as follows:

$$diS = \sum_i \frac{\gamma_i \cdot dN_{i-\tau}}{T_0}$$

where $t_1, t_2, ..., t_i$ are the validity periods of corresponding patent types.

Combining formulas (1) through (5), the expression for total entropy change in a technological system is:

$$dS = \sum_i \frac{\alpha_i \cdot dn_{i-0}}{T_0} - \sum_i \frac{\beta_i \cdot dN_{i-0}}{T_0} + \sum_i \frac{\gamma_i \cdot dN_{i-\tau}}{T_0}$$

4. Monitoring and Evaluation of Carbon Capture Technology

To further validate the effectiveness of the patent-based technology entropy analysis method, this study uses carbon capture and storage (CCS) technology as a case study. CCS technology refers to the technical means of capturing, separating, and permanently storing carbon dioxide from relevant emission combustion sources, which can be divided into three major technical fields: carbon capture, transportation, and storage. Among these, carbon capture can significantly reduce direct CO2 emissions and mitigate threats to global climate, making it considered an important pathway for deep greenhouse gas emission reduction. In recent years, the United States, Australia, Japan, and EU member states have conducted relevant basic research and feasibility trials, yet a series of technical bottlenecks continue to constrain CCS technology development. China faces enormous CO2 emission reduction pressure. Although actively restructuring its energy mix, fossil fuels represented by coal are widely believed to remain dominant in energy consumption in the short term. Therefore, carbon capture technology may become one of China' s important approaches to reducing carbon emissions. In fact, China began researching carbon capture technology as early as 2003, achieving major theoretical research progress and supporting the construction of several demonstration projects that, while still imperfect, have attracted widespread social attention. Carbon capture technology in China is currently in a rapid development period, with immature core technologies and uneven development across related technologies, making it a typical emerging technology.

Relying on the National Intellectual Property Administration' s Key Industries Patent Information Service Platform, we retrieved 2,861 data entries using the search terms "carbon dioxide and (adsorption or absorption or capture)" in patent abstracts, as shown in [Figure 1: see original paper]. We conducted technology entropy analysis on 2,716 patent applications from 1985–2013 to perform accurate and objective monitoring and analysis of carbon capture technology.

4.1 One-Dimensional Technology Entropy Analysis of Carbon Capture

The patent-based technology entropy model has strong applicability. To 梳理我国碳捕集技术的发展脉络 from a macro perspective, we employed the one-dimensional form of this model for technology entropy analysis.

With only the one-dimensional form, the original model simplifies to:

$$dS = \frac{\alpha \cdot dn_0}{T_0} - \frac{\beta \cdot dN_0}{T_0} + \frac{\gamma \cdot dN_{-\tau}}{T_0}$$

where x is the patent intensity coefficient (here equal to 1); α is the contribution rate of base-year patents to technology development (also 1 here due to lack of comparison); ε is the average patent authorization rate; and τ is the average patent application cycle, all calculated from publicly available patent application and acceptance data from the State Intellectual Property Office.

[Figure 2: see original paper] shows the analysis results of research intensity T_0 for China' s carbon capture technology from 1985–2013. The results indicate that China' s carbon capture technology research can be divided into three stages: Stage 1 (1985–1995): technological germination stage; Stage 2 (1996–2005): technology initiation stage; and Stage 3 (2006–2013): high-speed leap stage.

Based on the T_0 calculation results, this study further conducted technology entropy analysis on the low-speed development stage and high-speed leap stage, as shown in [Figure 3: see original paper].

[Figure 3: see original paper] reveals that although the low-speed development period (1996–2005) for carbon capture technology overall showed significant increases in patent volume and near-linear growth in research intensity, internal oscillations actually occurred within the technological system. In 1996, patent input higher than previous years provided excessive negative entropy for the carbon capture technology system, introducing disturbances that promoted system ordering. However, because the negative entropy input was initially still too small to generate macro-level movement, and the technological system inherently possessed self-organization properties that manifested as offsetting external influences, significant entropy production began to appear around 1999. The slowly strengthening negative entropy flow was insufficient to offset this impact, causing the technological system to tend toward stable equilibrium and manifest as 曲折发展. During this fluctuating development, continuously input negative entropy flow gradually brought the system into a near-critical state. Therefore, after experiencing fluctuations in 2005, disturbances in 2006 caused a qualitative change in the technological system, propelling it into a high-speed leap development stage (2006–2013). During this period, negative entropy flow continued to be input and consistently exceeded internal entropy production within the system, driving the system toward an unstable equilibrium state of technological maturity. However, it should be noted that in 2013, negative entropy flowing into the technological system decreased while entropy production suddenly increased, pulling the system back to a relatively balanced critical state. To identify future development directions for carbon capture technology, this paper conducted further research.

4.2 Two-Dimensional Carbon Capture Technology Entropy

Considering that the one-dimensional form of our model inadequately reflects micro-level fluctuations and is primarily used for trend analysis, we introduce the two-dimensional form of the patent-based technology entropy model here, analyzing invention patents and utility model patents as the first and second patent types, respectively. The original model becomes:

$$dS = \sum_{i=1}^{2} \frac{\alpha_i \cdot dn_{i-0}}{T_0} - \sum_{i=1}^{2} \frac{\beta_i \cdot dN_{i-0}}{T_0} + \sum_{i=1}^{2} \frac{\gamma_i \cdot dN_{i-\tau}}{T_0}$$

[Figure 4: see original paper] shows the analysis results of research intensity T_0 for China' s carbon capture technology from 1985–2013 under the two-dimensional system. Comparing [Figure 2: see original paper] and [Figure 4: see original paper] reveals that both model forms yield basically identical results for research intensity analysis. However, the two-dimensional model shows more pronounced 曲折上升趋势 during the low-speed development stage and exhibits different characteristics during the high-speed leap stage compared to the one-dimensional case, particularly the research intensity fluctuation in 2013 that warrants attention.

Using the two-dimensional technology entropy model to analyze the low-speed development stage and high-speed leap stage, [Figure 5: see original paper] illustrates China' s carbon capture technology development history from three perspectives: deS, diS, and dS.

From the deS perspective, since 1996, the entropy flow introduced into the system by new patents has generally manifested as negative entropy, with its growth increasing annually. During the low-speed development stage, because research intensity was relatively low, small patent inputs could bring significant entropy changes to the system, resulting in large negative entropy flows in certain years (e.g., 1997). Meanwhile, as stable patent input had not yet formed in this stage, some years (e.g., 1998) showed very small negative entropy flows or even positive values, well reflecting the 曲折上升 characteristics of the low-speed development stage. During the high-speed leap stage, annual patent input into the technological system grew steadily, research intensity increased year by year, and deS generally showed an upward trend except for individual years, revealing that carbon capture not only became a new research hotspot but also that China' s related research achieved certain results.

From the diS perspective, China's carbon capture technology system maintained a basically stable level during both the low-speed development and high-speed leap stages, with little variation between different years and values comparable to deS, reflecting that internal system effects were not yet strong enough—a typical characteristic of immaturity.

From the dS perspective, the boundaries between China' s carbon capture technology' s low-speed development stage and high-speed leap stage are clear. According to technology entropy theory, carbon capture technology during the high-speed leap stage experienced complete development and maturity stages and achieved important development (see [Figure 5: see original paper] and [Figure 6: see original paper]). However, comprehensive consideration of deS, particularly diS, leads to the conclusion that carbon capture technology has not yet matured.

[Figure 6: see original paper] shows the h value trend of carbon capture technology. In summary, China' s carbon capture technology is not yet mature. The important progress achieved during the high-speed leap stage provided necessary basic research and technology reserves for maturity. The reason dS tended toward 0 in 2013 is that although substantial research effort was invested, it did not yield high-level results comparable to previous levels. This indicates that China' s carbon capture technology development has entered a crucial stage where key technologies await breakthroughs, technology promotion needs strengthening, and industrialization capacity requires enhancement.

Further refinement of carbon capture technology-related patents reveals that the technical fields mainly involve classifications B01D, C01B, B01J, C07C, and

C10L, with patent numbers accounting for 87% of the total—highly representative. These five fields correspond to: (1) Performing operations; transporting—physical or chemical processes for separation; (2) Chemistry; metallurgy—inorganic chemistry—non-metallic elements and their compounds; (3) Performing operations; transporting—physical or chemical processes, e.g., catalysis, colloid chemistry and their apparatus; (4) Chemistry; metallurgy—organic chemistry—acyclic or carbocyclic compounds; and (5) Chemistry; metallurgy—petroleum, gas, and coke industries; industrial gases containing carbon monoxide; fuels; lubricants; peat—fuels not otherwise provided for; natural gas; synthetic natural gas obtained by processes not covered in C10G or C10K; liquefied petroleum gas; use of additives to fuels or fires; igniters.

Literature review reveals that all five fields are directly related to carbon capture materials but have limited association with carbon capture processes. Regarding applicant composition, patent applications from Zhejiang University, China Petroleum & Chemical Corporation, Southeast University, Toshiba Corporation, Tsinghua University, Alstom Technology Ltd., East China University of Science and Technology, and Dalian University of Technology account for 86% of the total. Domestic research institutions are mostly universities, with only one domestic enterprise. These two points indicate that China' s carbon capture research mostly concentrates on primary stages such as absorption and adsorption materials, with research institutions still dominated by universities and insufficient involvement from domestic enterprises, suggesting the country does not yet possess large-scale industrialization capacity.

4.3 Dynamic Evaluation of Carbon Capture Technology Development

According to technology entropy theory, technology development is influenced by numerous factors including policy, economy, and market, making its real development path almost unpredictable. Therefore, this paper proceeds from technology entropy, relies on existing data, and conducts dynamic evaluation of China' s carbon capture technology development through single-variable analysis.

(1) Assuming that by 2020, China' s carbon capture technology-related patent application and publication volumes remain at the average level of 2011–2013, the dS development situation is shown in Figure 7: see original paper. Under this scenario, deS will reach a stable level starting in 2014, but diS will increase rapidly, with dS always positive, leading to severe system degradation and eventual extinction.

(2) According to the technology entropy patent model, we relax assumption (4) regarding the quantitative relationship between research intensity T and patent volume, i.e., maintaining high attention to carbon capture while not all technical achievements manifest as patent growth. Assuming T grows at the average growth rate of 2009–2013 during 2014–2020, the dS development situation is shown in Figure 7: see original paper. Under this

scenario, both deS and diS will decrease year by year, but deS decreases faster than diS, with dS always positive, causing the system to rapidly move toward extinction.

(3) Assuming that by 2020, China' s carbon capture technology-related patent application and publication volumes grow linearly at the average growth volume of 2009–2013, the dS development situation is shown in Figure 7: see original paper. Under this scenario, both deS and diS will accelerate growth at basically the same rate, with dS fluctuating near 0, causing the technological system to re-enter a low-speed development stage similar to 1996–2005 and making substantive progress difficult.

(4) Assuming that by 2020, China' s carbon capture technology-related patent application and publication volumes grow exponentially at the average growth rate of 2009-2013, the dS development situation is shown in Figure 7: see original paper. Under this scenario, both deS and diS will accelerate growth, but deS grows significantly faster than diS, with dS showing negative values that effectively drive technology toward maturity.

Single-variable analysis reveals that China' s carbon capture technology is at a critical development stage, with development in the coming years directly affecting the entire technological system' s evolution. Since the system itself is still in the development stage, if negative entropy input falls below internal entropy production, the technological system will rapidly degrade until extinction, with technologies accumulated over the previous decade dispersing into different fields rather than forming a carbon capture technology system. If negative entropy input matches internal entropy production levels, the system will maintain an unstable equilibrium but cannot reach maturity, requiring increasingly more negative entropy input to sustain the system' s dissipation at higher costs. Once negative entropy flow decreases, the system faces rapid degradation risk, representing a high-input, low-return situation. If negative entropy input exceeds internal entropy production, the system will enter a new development process, depending on a series of technological innovations driven by core technology breakthroughs to push technology toward maturity, with the degree of evolution directly determining the industrialization potential of China' s carbon capture technology.

5. Conclusion

This study introduces the concept of entropy into patent-based technological systems and proposes a technology entropy analysis method. Using China' s emerging carbon capture technology as an example, we constructed one-dimensional and two-dimensional patent technology entropy models to monitor and evaluate the overall development of China' s carbon capture technology, validating the effectiveness of the patent-based technology entropy analysis method in emerging technology monitoring and evaluation applications. Analysis of carbon capture technology yields the following main conclusions:

(1) From 1985–2013, China' s carbon capture technology research experienced technological germination, low-speed development, and high-speed leap stages. Although the low-speed development period (1996–2005) overall showed significant increases in patent volume and near-linear growth in research intensity, internal oscillations actually occurred within the technological system, representing 曲折上升. Around 2006, carbon capture technology began rapid development based on previous foundations, entering a critical development stage by 2013.

(2) From the *deS* perspective, carbon capture technology has not only become a new research hotspot but also achieved certain results. From the *diS* perspective, the technology system still exhibits typical characteristics of immaturity. Therefore, China' s carbon capture technology is not yet mature. The important progress achieved during the high-speed leap stage provided necessary basic research and technology reserves for maturity. However, substantial recent research investment has not yielded high-level results comparable to previous levels, confirming that China' s carbon capture technology development has entered an important stage where key technologies await breakthroughs, technology promotion needs strengthening, and industrialization capacity requires enhancement.

(3) Analysis reveals that 87% of China' s carbon capture technology-related patents mainly relate to carbon capture materials, and among the 86% of applying institutions, only one is a domestic enterprise. This indicates that China' s carbon capture research mostly concentrates on primary stages such as absorption and adsorption materials, research institutions are still dominated by universities, domestic enterprise involvement is insufficient, and large-scale industrialization capacity is not yet established.

(4) Single-variable analysis shows that development in the coming years will directly affect the entire carbon capture technology system' s evolution. Core technology breakthroughs and resulting technological innovations can effectively drive technology toward maturity, with the degree of evolution directly determining the industrialization potential of China' s carbon capture technology.

(5) To comprehensively promote China' s carbon capture technology development, research management departments should focus more on concentrating efforts to tackle key technologies awaiting solutions to open up new situations. Researchers could attempt to conduct equipment and process studies to eliminate technological weaknesses and prepare technically for industrial carbon capture implementation. Enterprises should not only closely monitor relevant research trends but also appropriately increase R&D investment to develop technologies more closely connected with enterprise needs and improve patent technology applicability.

The research conclusions demonstrate that the patent-based technology entropy analysis method, proceeding from a technological system perspective and analyzing changes in system elements, overall reveals evolution trends in technology domains and determines technology lifecycle stages, serving as an effective tool for monitoring technological systems.

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Author Contributions

Hou Jianhua: Conceived the research idea, designed the research framework, wrote the paper, and revised the final version.
Guo Shuang: Conducted data retrieval and processing, designed case studies and performed analysis.

Conflict of Interest

All authors declare no conflict of interest.

Supporting Data

The supporting data is self-archived by the authors and available upon request at houjianhua@dlu.edu.cn.

[1] Hou Jianhua. Experimental raw data from the National Intellectual Property Administration Key Industries Patent Information Service Platform http://www.chinaip.com.cn.

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Note: Figure translations are in progress. See original paper for figures.