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Technological Innovation Efficiency of Listed Carbon Capture Companies in China: Based on the Dual Dimensions of Legal Policy and Technology

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Abstract: To achieve carbon neutrality and improve emission reduction efficiency, capturing carbon dioxide from the air on a large scale and promoting the application and innovation of carbon capture technology (CCUS) are the most important goals. This study undertakes an annual and comprehensive evaluation of the policy and the technological innovation efficiency (TIE) of 10 listed companies in China using the DEA model and the Malmquist index analysis method. The number of relevant laws and policies is significant, but they are not well coordinated. The static evaluation results indicate that the complete factor production rate is low, generally lower than 0.9, and the technical innovation efficiency is weak, mainly because of technological backwardness. The dynamic evaluation results indicate that the changes in total factor productivity (TFP) each year are primarily affected by changes in technological progress. This suggests that most domestic enterprises are still exploring technological innovation (TI) and operational business models. Finally, this study proposes measures to improve the TIE of carbon capture technology enterprises in China, including giving full play to the role of the government, expanding effective investment, and improving innovational ability.

Keywords: CCUS; carbon neutrality; DEA; Malmquist

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Citation: Xu, X.; He, D.; Wang, T.; Chen, X.; Zhou, Y. Technological Innovation Efficiency of Listed Carbon Capture Companies in China: Based on the Dual Dimensions of Legal Policy and Technology. *Energies* **2023**, *16*, 1118. https://doi.org/10.3390/en16031118

Academic Editors: Zilong Liu, Meixia Shan and Yakang Jin

Received: 2 October 2022
Revised: 5 November 2022
Accepted: 22 November 2022
Published: 19 January 2023

1. Introduction

The dual-carbon target strategy is a requirement for China to promote high-quality development. Whether China's dual-carbon goal strategy can be successfully realized depends on the effect of specific policies after implementation. The government needs to formulate administrative regulations and departmental rules to restrict the carbon emission behavior of emission control enterprises [1]. The market mechanism can ensure carbon emission reduction in the most cost-effective way and, at the same time, promote the enterprise innovation of emission reduction technology to control the total carbon emission [2]. Therefore, achieving the dual-carbon goal needs the help of government-level administrative regulations, market-level price mechanisms, and TI. Government departments can promote the short-term carbon peaking goal by formulating administrative rules [3]. However, from the perspective of long-term planning, increasing emission reduction motivation will breed movement-style carbon reduction behavior. The carbon market price signal has a significant role in promoting short-term carbon emission reduction behavior. However, in the long run, TI is still the fundamental way to achieve the dual-carbon goal [4].

Carbon dioxide capture, utilization, and storage (CCUS) refers to the capture and separation of CO_2 from energy utilization, industrial processes, and other emission sources or air and transporting it to suitable sites for utilization or storage by tankers, pipelines, ships, etc., ultimately achieving CO_2 emission reduction. It is necessary for China to achieve carbon peaking and carbon neutrality. CCUS technology can not only achieve near-zero emissions from fossil energy utilization but also promote profound emission reduction in industries such as steel and cement where emission reduction is difficult. Moreover, it is vital to enhance the flexibility of the power system under carbon constraints, ensure a safe and stable power supply, offset the CO_2 and non-CO_2 greenhouse gas emissions that are difficult to reduce, and finally achieve the goal of carbon neutralization. In recent years, carbon capture, utilization, and storage (CCUS) has received extensive attention from the international community as a critical technology for mitigating climate change. Researchers have focused on the emission reduction potential, cost, and application prospects of CCUS. The technology was systematically and comprehensively evaluated. The conclusion was that CCUS technology is an indispensable combination of emission reduction technologies for the realization of global climate goals and has the potential to achieve a cumulative emission reduction effect of 100 billion tons by the middle of the 21st century. The emission reduction potential must be further increased. Considering that CCUS can effectively reduce the risk of stranded assets and offers social and environmental benefits, China should take CCUS as a strategic technology and coordinate its top-level policy based on its resource endowment and the primary national conditions of "rich coal, poor soil, and little gas". China must design and accelerate the construction of technical systems, explore market incentives, strengthen international cooperation, and promote the development of CCUS technology.

For companies that conduct research and development in carbon capture technology, there will also be rewards, including improved reputation and economic benefits. For example, Guanghui Energy announced that it plans to invest in the construction of an integrated project for three million tons of carbon dioxide capture, pipeline transportation, and oil displacement. In terms of energy acquisition, China is currently highly dependent on coal for power generation and is the world's largest steel producer. Relevant assessments indicate that natural gas and coal power generation using CCUS technology are less cost competitive and may not be cost competitive with other renewable energy sources. In addition to cost factors, large-scale deployment of CCUS faces different challenges, such as environmental risks, technical challenges, lack of funding, social opposition, and policy uncertainty. Other, more cost-competitive low- or zero-emission options may emerge, and CCUS will become less attractive. Of course, the emergence of new low-carbon technologies is speculative, and their applicability will need to be tested in practice. Overall, the current CCUS technology is still in the stage of conception to experimentation, and there is still a long way to go before large-scale commercial application. Therefore, we considered China's listed companies with carbon capture-related technologies as samples, modeled their R&D investment and financial data, and explored the TIE and influencing factors of carbon capture technology companies. The innovation of this paper is in conducting an empirical study on the profit of carbon capture technology companies using carbon capture technology innovation; if carbon capture technology can lead to an increase in corporate profits, then related companies will have more significant incentives to engage in its development and utilization.

During the past few years, relevant policies and guidelines have been successively issued, including the Outline of the National Medium- and Long-Term Science and Technology Development Plan, China's Climate Change Action Plan, and China's Special Action on Climate Change Science and Technology, etc., clearly proposing CCUS technology as an essential plan and key development technology for future national development. At the same time, the Chinese CCUS Technology Development Roadmap Research was also issued, which is a series of policies to guide and encourage large domestic energy companies in carrying out R&D demonstration projects. Currently, China clearly defines CCUS technology as a significant demonstration project to guide and support carbon peaks and carbon neutralization work, which requires the promotion of large-scale CCUS technology research and industrial application.

2. Literature Review

2.1. CCUS Technologies Review

2.1.1. Development Status of Carbon Capture Technology

Carbon capture is the first link in CCUS and the main cost source in the CCUS process. Carbon is mainly captured from industrial exhaust gases and the atmosphere, and the higher the CO_2 concentration, the lower the capture cost. According to the order of carbon capture and combustion, carbon capture technologies can be divided into pre-combustion capture, post-combustion capture, and oxy-fuel combustion capture [5]. The cost of pre-combustion capture is relatively low, and the efficiency is high, but the applicability is not high. Although post-combustion capture is widely used, it has higher relative energy consumption and cost. Oxy-fuel combustion has high requirements for the operating environment and is still in the demonstration stage. According to the separation process, carbon capture technology is mainly divided into physical absorption technology, chemical absorption technology, membrane separation technology, low-temperature separation technology, etc. [6].

Carbon utilization is key to reducing the cost of CCUS implementation. Currently, geological utilization is the primary mode in China, and chemical and biological utilization are relatively rare. Specifically, CO_2-EOR technology in geological utilization can sequester a large amount of CO_2 and increase oil production, considering the economic and environmental benefits, and has high feasibility in the short term [7]. Chemical utilization is based on the main characteristics of chemical conversion, converting CO_2 and reactants into target products to achieve resource utilization; it has low requirements for CO_2 concentration and common implementation cost, which has development value. Bioutilization is the primary means of biological conversion; when using CO_2 for biomass synthesis, the concentration of CO_2 is high, and the implementation cost is high, but the yield per ton of CO_2 is also relatively high.

However, CO_2 emissions far exceed their utilization capacity, and the CO_2 that cannot be used must be stored using storage technology. Carbon sequestration is mainly divided into technologies such as saline aquifer storage and depleted oil and gas reservoir storage [8]. Between them, the saline water layer is widely distributed and has good closure and the ideal storage effect. Depleted oil and gas reservoirs usually have a complete, closed, and stable geological environment, which can ensure the safety of storage. Still, there is a particular risk of leakage, requiring multi-directional monitoring technology.

2.1.2. Research Status of Carbon Capture Technology

M. Paweł reviewed the research on various CCUS technologies, summed up the advantages and development constraints of different technologies, and proposed a CCUS technology with good application prospects, pointing out that in the future, CCUS technology urgently needs to strengthen the research on cost and risk control. Developing new materials and TIs will boost the development of this technology. At the same time, multi-scale monitoring technology will ensure the safety of the entire project implementation and provide effective solutions for alleviating global warming [9]. P. Wienchol focused on three typical thermal power and cement industries and summarized the overall development of CCUS in the three specific initiatives. It was pointed out that the application of CCUS technology in specific industries in China is still in the early stage of development, and the synergistic effects of CCUS technology (such as increased energy consumption in thermal power plants, reaction with products in cement plants, etc.), installation costs, environmental impacts, and risks are all limits to the large-scale application of CCUS. It was recommended to refine the emission reduction technology plans for thermal power, steel, and cement industries, provide exceptional funding support for CCUS technology R&D and demonstration projects in specific industries, and further promote the integrated demonstration and commercial application of the CCUS chain [10]. Chenggang Wang conducted research and found that improving carbon capture technology will drive enterprises' TIE development [11]. Gao found an inverted U-shaped relationship between intellectual property protection and manufacturing technical efficiency. Strengthening intellectual property protection at this stage can significantly improve the technical efficiency of China's manufacturing industry [12]. Yang used CiteSpace software to quantitatively analyze the CCUS technology patents in the Derwent patent database and pointed out that the United States and China are the major CCUS technology research countries, and most of China's patent holders are universities and institutions [13]. Waste gas treatment and CO_2 flooding are the hot technologies for CCUS patents; in carbon capture, the hot technology is desorption tower technology, and converting CO_2 into inorganic salts using calcium-containing compounds is an emerging field. In carbon utilization technology, CO_2 is used to generate carbon fiber. As a hot technology, mixed utilization is an innovative research direction; in carbon sequestration, the technical patents for tanks and release devices are hot technologies, and packaging technologies in different environments and device inventions for transportation are new research directions.

2.2. Review of TI

Through a study of the literature, we found that TI research fields have mainly concentrated on three aspects. One is the influence of internal and external factors on innovation activities. The second is the analysis of the TI capability of companies. The third is researching methods of measuring the efficiency of TI.

2.2.1. Research on the Influencing Factors of TI

An in-depth analysis of the factors that affect the TI of enterprises can give us a deeper understanding of the development level of the TI field of enterprises. Therefore, scholars have been focused on "factors affecting TI of enterprises" and divided the influencing factors into two aspects: external and internal. Regarding the research on external influencing factors, Yana Rubashkina found that rules and regulations promulgated by the government play an essential role in TI through a study of European manufacturing enterprises [14]. Wu found in his study that the national rules and regulations have a specific promotional effect on the innovation performance of enterprises [15]. Hong analyzed innovation from the perspective of efficiency. He found that the efficiency of enterprise TI is negatively correlated with government support, and the increase in subsidies will reduce the efficiency of TI [16]. Bigliardi et al. performed the same research and proved a significant relationship between government subsidies and TIE [17]. From the perspective of internal influencing factors, Dabic found that the degree of internationalization positively affects the innovation of enterprises. As the degree of internationalization increases, the knowledge and technology absorbed will encourage the enterprise to better carry out innovation activities [18]. Through research on pharmaceutical companies, Laermann-Nguyen discovered a specific relationship between independent innovation ability and TI ability [19]. Shearmur took export enterprises as the object of investigation and analysis and found that, compared with non-export enterprises, export enterprises have a higher level of innovation that is proportional to their export scale [20]. Through the above research, we gained a good understanding of the various factors that affect the efficiency of enterprise TI, but more in-depth research is needed.

2.2.2. Research on the Evaluation of TI Capability

Sumrit and Detcharat researched management capabilities, established a scientific comprehensive evaluation model, and concluded that management capabilities can promote

TI capability improvement [21]. Hai conducted research on the automobile industry as an example, established a TIE evaluation model, and concluded that the TIE of the automobile industry is not ideal. The scale of innovation input cannot obtain good returns for output and should be increased. Investing in large-scale innovative talents also requires increased government subsidies and the emphasis on output capacity, as well as relevant strategies to promote the rapid development of the industry [22]. C. Feniser used the classic theory of TRIZ to analyze enterprises regarding the two aspects of risk management and TI and constructed a reasonable and complete innovation evaluation system [23]. K. Lee studied and evaluated the TI of SMEs using the hidden Markov model and Viterbi algorithm and determined in-depth related indicators [24]. Through the analysis and summary of the above literature, we found that scholars cannot test TI's ability without the selection and analysis of influencing factors. We discovered that research on TI and related influencing factors is essential.

2.2.3. Related Research on TI Evaluation Methods

There are many methods to study the efficiency of TI, such as DEA, stochastic frontier analysis, Tobit method, etc. By reading the relevant literature, we summarized the methods for studying the efficiency of TI of enterprises as follows. Wang used the Malmquist index analysis method to evaluate the TIE of manufacturing enterprises and found the main influencing factor that promotes TIE [25]. Lanoie's research determined that government environmental policies positively impact environmental efficiency, and different policy intensities have heterogeneous effects [26]. Wong's research indicated that the positive impact of green process innovation on green innovation efficiency and revenue is evident, while green product innovation is negative. Wong proposed that green innovation includes product and process innovation [27]. Ghisetti and Rennings evaluated green innovation efficiency in energy consumption and environmental pollution [28]. Zhang used the input–output method to evaluate the input–output ratio of TI of industrial enterprises and conducted a comparative study [29]. Guo and Yang evaluated the efficiency of green innovation in each region [30]. Liu et al. researched the sustainability of the coal industry, taking environmental, production, and other factors into account [31]. Wang pointed out that the lag in environmental efficiency has a hindering effect on TIE [32]. Using a case study approach, Rumanti devised a new model for green innovation. For other assessments related to green innovation, see [33]. Govindan et al. reviewed multi-criteria decision-making methods for evaluating and selecting suppliers using green technology [34]. Sun et al. used the TOPSIS method to establish a model to evaluate the impact of TIE on the ecology and economic benefits [35]. Guo evaluated the level of green technology innovation from the perspective of green development and discussed the role of government environmental regulation [36]. Lin used the DEA method to assess green technology's innovation efficiency in 28 manufacturing industries in China from 2006 to 2014 [37]. The research of Lee and Choi suggested that the innovation effect leads to environmental productivity in the Korean manufacturing industry. Not only should each sector strive to improve performance, but the government must also formulate specific measures to improve overall competitiveness [38].

2.3. Current Status of Laws and Policies on Carbon Capture Technology in China

Currently, China has relatively comprehensive rules and regulations in energy conservation and emission reduction, clean and renewable energy. However, CCUS technology is still a blank page [39]; laws such as the Environmental Protection Law, Administrative Penalty Measures for Environmental Protection, the Environmental Impact Assessment Law, and the Water Pollution Prevention and Control Law do not include CCUS technology-related content. There is no CCUS legal framework for enterprises to refer to in their policies and measures. The entire CCUS chain involves different industries and departments, including national, local, enterprise, petroleum, coal, electric, chemical industry, etc. A corresponding regulatory system, overall coordination mechanism, and industrialization layout guidance policy have not been issued, especially regarding CCUS technology [40]. After realizing that the economic incentive measures for carbon emission reduction, the long-term high-cost investment and low-profit return will inevitably lead to a long-term profit and loss imbalance after enterprises carry out large-scale CCUS projects; enterprises have chosen to carry out small or no CCUS projects, which has greatly hindered the advancement of CCUS technology in China.

3. Model and Index Selection

3.1. Model

This study mainly adopted the data envelopment analysis (DEA) model with the non-parametric method, which integrates mathematics, operation research, and other contents and is a standard method for evaluating relative effectiveness in economics. Compared with traditional data analysis, DEA greatly reduces the influence of human factors and improves the objectivity of the evaluation results; thus, the relative efficiency obtained is more practical. According to the factors of production rate, scale efficiency, pure technical efficiency, and redundancy rate of DEA output, optimization directions and approaches can be proposed in a targeted manner. This paper mainly used the input-oriented variable returns to scale (VRS) DEA-BCC analysis model (which was put forth by Banker, Charness, Cooper) and the DEA-Malmquist index model to evaluate the TIE of China's carbon capture-listed companies. In this way, we could explore whether enterprises obtained better income by engaging in carbon capture technology innovation. The typical and commonly used data envelopment analysis (DEA) methods are CCR (which was put forth by Charnes, Cooper, and Rhodes) and BCC models:

$$\min\left[\theta - \varepsilon\left(e^{-}S^{-} + e^{+}S^{+}\right)\right] \; s.t. \left\{ \begin{array}{c} \sum\limits_{j=1}^{n} x_j\lambda_j + S^{-} = \theta x_k \\ \sum\limits_{j=1}^{n} y_j\lambda_j - S^{+} = y_k \\ \lambda \gg 0, j = 1, 2, \ldots\ldots, n \\ S^{+} = \left(S_1^{+} S_2^{+}, S_3^{+}, \ldots S_q^{+}\right)^T \gg 0 \\ S^{-} = \left(S_1^{-} S_2^{-}, S_3^{-}, \ldots, S_p^{-}\right)^T \gg 0 \end{array} \right\}$$

In the formula: θ is the technical efficiency value, $0 \leq \theta \leq 1$; ε is the non-Archimedes infinitesimal; S^{-}, $S^{+} \geq 0$ are the input and output slack variables, respectively; e T1 is the m-dimensional unit vector; e T2 is an n-dimensional unit vector; $\lambda_i \geq 0$ is a weight variable; x is the j input of the j decision-making unit; y_j is the m output of the j decision-making unit.

Banker, Charnes, and Cooper considered that the decision-making unit could not produce at the optimal production scale because of factors such as imperfect competition and capital constraints in practice, so they improved the CCR model. They introduced controls into the model and proposed a BCC model with variable returns to scale. In addition, DEA requires that the data must be cross-sectional data at the same time as evaluating the relative efficiency of the unit, and the time dimension cannot be introduced for analysis. To solve this problem, the Malmquist index was introduced to analyze the cross-sectional data in the time dimension, that is, panel data. Therefore, the dynamic change law of the technical efficiency of the evaluation unit can be obtained.

The Malmquist index is called the TFP index (TFP), which Sten first proposed in 1953 to analyze the data changes in different periods more vividly. Later, through the continuous improvement by scholars such as Charnes based on DEA, the DEA-Malmquist index model was further decomposed, including four parts: technological progress change, technical efficiency change, pure technical efficiency changes, and scale efficiency change.

$$\mathrm{M}(x_t, y_t, x_{t+1}, y_{t+1}) = \frac{D^{t+1}(x_{t+1}, y_{t+1})}{D^{t}(x_t, y_t)} \times \left[\frac{D^{t}(x_{t+1}, y_{t+1})}{D^{t+1}(x_{t+1}, y_{t+1})} \times \frac{D^{t}(x_t, y_t)}{D^{t+1}(x_t, y_t)}\right]^{\frac{1}{2}} = \mathrm{EFFCH} \times \mathrm{TECH}$$

The results determine the dynamic changes in efficiency between different periods, which can not only indicate the changes in the overall year but also help to analyze the differences of each decision-making unit between years. The DEA-Malmquist index model and the DEA model can form complementary effects. The DEA model measures the efficiency value of each decision-making unit in a period but cannot observe the change of each decision-making unit in a period. The DEA-Malmquist index model can make up for this shortcoming and keep the evolution of the efficiency value of each enterprise in the time series. Therefore, this paper first constructed a DEA model to conduct a static analysis of the measurement results of each enterprise and, second, created a DEA-Malmquist index model to perform a dynamic analysis of the measurement results of each enterprise from 2018 to 2021. The TIE value of China's carbon capture listed companies can be measured from two aspects, dynamic and static, to reveal their TI capabilities more comprehensively.

3.2. Variable Selection

3.2.1. Study Area and Data Source

As shown in Table 1, we selected the data of 10 listed companies from 2018 to 2021 as the research area. At the same time, when collecting and arranging relevant data, the primary data sources were the official websites of the SHSE and SZSE and the WIND and Cathay Pacific databases.

Table 1. Panel data sample of carbon capture technology listed companies.

Company Name	Securities Code
Moon Environment Technology Co., Ltd.	000811
Hangzhou Oxygen Plant Group Co., Ltd.	002430
Xizi Clean Energy Equipment Manufacturing Co., Ltd.	002534
Hunan Kaimeite Gases Co., Ltd.	002549
Sunresin New Materials Co., Ltd.	300487
SPIC Yuanda Environmental-Protection Co., Ltd.	600292
Haohua Chemical Science and Technology Co., Ltd.	600378
Wuxi Huaguang Environment and Energy Group Co., Ltd.	600475
Shuangliang Eco-energy Systems Co., Ltd.	600481
Guanghui Energy Co., Ltd.	600256

3.2.2. Selection of Input–Output Indicators

As shown in Table 2, the selection of indicators is an indispensable step in empirical research, and the scientific degree of their selection has an important influence on the realization of the research purpose [25]. The carbon capture technology industry has the characteristics of strong dependence on environmental protection, and it is an industry that is highly dependent on policies and has more concentrated R&D resources. The domestic market demand continues to expand with the continuous improvement of carbon neutrality target policy requirements. In the face of a broad market, a product or TI is regarded as a decisive factor in the competition among carbon capture technology companies. The earlier companies can develop advanced carbon capture technologies, the more likely they are to occupy a larger market share. Concerning the technical innovation efficiency articles for the relevant listed companies, the specific indicators constructed by the relevant research were sorted out, and the characteristics of the carbon capture technology industry itself were considered. The input indicators screened in this paper included the number of R&D employees and R&D expenses; output indicators included patent licensing volume and operating income. The specific list is as follows:

Table 2. Input–output indicators of the TI of carbon capture technology enterprises.

	Indicator Name	Symbol
Input indicators	R&D expenses	X1
Input indicators	Number of R&D employees	X2
Output indicators	Main business income	Y1
Output indicators	Number of patents granted	Y2

4. Results and Analysis

4.1. Static Analysis

4.1.1. Data Analysis in 2018

As shown in Table 3, in 2018 the average technical efficiency (ATE) was 0.2342, the average pure technical efficiency (APTE) was 0.4809, and the average scale efficiency (ASE) was 0.5229. The low innovation efficiency was the result of the combination of pure technical efficiency and scale efficiency, and APTE was the main reason, with the upside close to 52%. According to the results, only Guanghui Energy had a technical efficiency of 1, which was at the frontier of efficiency. There was no enterprise with a technical efficiency between 0.9 and 1, indicating a trend of polarization among the listed companies. The TIE of other enterprises was relatively weak. Among them, Sunresin New Materials had the lowest score, and the technical efficiency was only 0.0053. Compared with the traditional lithium extraction technology, the DLE technology with independent intellectual property rights of Sunresin New Materials was more efficient and low-carbon, did not use any solvent, and would not affect the aquifer in the salt-lake area. Still, the technical level needed further improvement. The technical efficiency of most enterprises was even less than 0.5.

Table 3. 2018 Enterprise Data.

Firm	Crste	Vrste	Scale	
Moon Environment Technology Co., Ltd.	0.116	0.16	0.723	drs
Hangzhou Oxygen Plant Group Co., Ltd.	0.126	0.809	0.156	drs
Xizi Clean Energy Equipment Manufacturing Co., Ltd.	0.073	0.106	0.69	drs
Hunan Kaimeite Gases Co., Ltd.	0.084	0.492	0.171	irs
Sunresin New Materials Co., Ltd.	0.053	0.356	0.149	irs
SPIC Yuanda Environmental-Protection Co., Ltd.	0.298	0.347	0.858	irs
Haohua Chemical Science and Technology Co., Ltd.	0.122	0.357	0.34	drs
Wuxi Huaguang Environment and Energy Group Co., Ltd.	0.321	1	0.321	drs
Shuangliang Eco-energy Systems Co., Ltd.	0.149	0.182	0.821	drs
Guanghui Energy Co., Ltd.	1	1	1	-
mean	0.2342	0.4809	0.5229	

The pure technical efficiency of Wuxi Huaguang, Environment and Energy Group, reached 1, indicating that this enterprise's low technical efficiency value was mainly affected by scale efficiency. The scale efficiency of Shuangliang Eco-energy Systems and SPIC Yuanda Environmental-Protection was above 0.8, indicating that the technical inefficiency of these two enterprises was mainly due to the influence of pure technical inefficiency. SPIC Yuanda Environmental-Protection Company's business focuses on the general contracting of desulfurization, denitrification, dust removal projects, desulfurization and denitrification franchise operations, water engineering and operations, catalyst manufacturing and regeneration, ecological restoration projects, and dust collector equipment manufacturing and installation. It is at the forefront of the industry and has the first domestic 10,000-ton carbon capture device in Hechuan, Chongqing. It was prominent in scale but lacked TI.

In addition, the companies that had not reached the frontier were basically in a state of decreasing scale, and insufficient TI constrained their efficiency value.

4.1.2. Data Analysis in 2019

As shown in Table 4, the TIE in 2019 was not much different from the previous year, with an ATE of 0.1271, an APTE of 0.4261, and an ASE of 0.415. The main reason for the inefficiency of innovation was the combination of PTE and SE. According to the results, the technical efficiency of all enterprises was lower than 0.2, which was relatively low. This was not much different from the previous year, indicating the same problems in 2018 and 2019. Except for Haohua Chemical Science and Technology, whose pure technical efficiency reached 0.838, the TIE of other companies was relatively weak. Among them, Xizi Clean Energy Equipment Manufacturing was the company with the lowest score of only 0.059. Among them, the scale efficiency of Hangguo and SPIC Yuanda Environmental-Protection reached 0.9, indicating that the low technical efficiency value of these two companies was mainly affected by pure technical efficiency. Xizi Clean Energy Equipment Manufacturing mainly produces waste heat boilers that use waste heat from various industrial processes, wastes, or waste liquids and the heat generated by the combustion of combustible substances to heat water to a working quality. The business of Xizi Clean Energy is mainly equipment manufacturing. It focuses on the sun's thermal energy to generate electricity, which may be one reason its carbon capture technology is progressing more slowly. Unlike the previous year, among the companies that did not reach the frontier in 2019, there were more companies with increasing returns to scale, indicating that some companies were actively adjusting the structure of corporate resource investment, but the effect was not yet apparent.

Table 4. 2019 Enterprise Data.

Firm	Crste	Vrste	Scale	
Moon Environment Technology Co., Ltd.	0.14	0.339	0.412	drs
Hangzhou Oxygen Plant Group Co., Ltd.	0.079	0.665	0.118	drs
Xizi Clean Energy Equipment Manufacturing Co., Ltd.	0.058	0.059	0.971	irs
Hunan Kaimeite Gases Co., Ltd.	0.121	0.386	0.314	irs
Sunresin New Materials Co., Ltd.	0.045	0.187	0.239	irs
SPIC Yuanda Environmental-Protection Co., Ltd.	0.175	0.183	0.955	irs
Haohua Chemical Science and Technology Corp., Ltd.	0.184	0.838	0.219	drs
Wuxi Huaguang Environment and Energy Group Co., Ltd.	0.166	0.733	0.227	drs
Shuangliang Eco-energy Systems Co., Ltd.	0.181	0.445	0.408	drs
Guanghui Energy Co., Ltd.	0.122	0.426	0.287	drs
mean	0.1271	0.4261	0.415	

4.1.3. Data Analysis in 2020

As shown in Table 5, the TIE of listed companies in 2020 slightly improved compared to the previous year. The ATE was 0.1708, APTE was 0.5749, and ASE was 0.4259. There was large room for improvement in SE and PTE. According to the results, the technical efficiency of Guanghui Energy dropped to 0.069, but its scale efficiency was 0.990, indicating that the decline in its technical efficiency was mainly affected by the low PTE, which was only 0.069. The score of Sunresin New Materials was the lowest at only 0.046, which was not much different from the scores of the previous two years. Moon Environment Technology mastered the core technologies of the −271 to 800 °C temperature range, 0~90 MPa full pressure, from the conventional single working fluid to mixed working fluid and slight molecule special gas compression. It continues to lead the technological progress of the industry. In technical services, Haohua Chemical Science and Technology has apparent advantages in pressure swing adsorption gas separation technology (PSA), and it is one of the world's three largest PSA technology service providers. It can also be seen from the table that the PTE of Binglun Environment and Haohua Chemical Science and Technology reached 1, indicating that the low technical efficiency values of these two companies were mainly affected by scale efficiency.

Table 5. 2020 Enterprise Data.

Firm	Crste	Vrste	Scale	
Moon Environment Technology Co., Ltd.	0.229	1	0.229	drs
Hangzhou Oxygen Plant Group Co., Ltd.	0.089	0.888	0.1	drs
Xizi Clean Energy Equipment Manufacturing Co., Ltd.	0.101	0.527	0.191	drs
Hunan Kaimeite Gases Co., Ltd.	0.399	0.512	0.78	drs
Sunresin New Materials Co., Ltd.	0.046	0.213	0.218	irs
SPIC Yuanda Environmental-Protection Co., Ltd.	0.123	0.144	0.857	irs
Haohua Chemical Science and Technology Corp., Ltd.	0.172	1	0.172	drs
Wuxi Huaguang Environment and Energy Group Co., Ltd.	0.276	0.908	0.303	drs
Shuangliang Eco-energy Systems Co., Ltd.	0.204	0.488	0.419	drs
Guanghui Energy Co., Ltd.	0.069	0.069	0.99	irs
mean	0.1708	0.5749	0.4259	

4.1.4. Data Analysis in 2021

As shown in Table 6, in 2021 the TIE of listed companies dropped slightly again, with an ATE of 0.1544, an APTE of 0.6515, and an ASE of 0.2909. However, there was still room for an improvement in scale efficiency of nearly 70%. According to the results, the technical efficiency of Hunan Kaimeite Gases was relatively high. It was only 0.435, but its pure technical efficiency reached 0.925, which was high, indicating that scale efficiency was its main factor. Kaimet Gas is a listed company that uses the tail gas (waste gas) and flare gas emitted by petroleum and petrochemical enterprises as raw materials, and separates, purifies, and recycles the valuable components.

Table 6. 2021 Enterprise Data.

Firm	Crste	Vrste	Scale	
Moon Environment Technology Co., Ltd.	0.198	1	0.198	drs
Hangzhou Oxygen Plant Group Co., Ltd.	0.102	1	0.102	drs
Xizi Clean Energy Equipment Manufacturing Co., Ltd.	0.045	0.436	0.104	drs
Hunan Kaimeite Gases Co., Ltd.	0.435	0.925	0.471	drs
Sunresin New Materials Co., Ltd.	0.056	0.152	0.371	irs
SPIC Yuanda Environmental-Protection Co., Ltd.	0.139	0.214	0.653	drs
Haohua Chemical Science and Technology Corp., Ltd.	0.124	1	0.124	drs
Wuxi Huaguang Environment and Energy Group Co., Ltd.	0.257	1	0.257	drs
Shuangliang Eco-energy Systems Co., Ltd.	0.09	0.194	0.464	drs
Guanghui Energy Co., Ltd.	0.098	0.594	0.165	drs
mean	0.1544	0.6515	0.2909	

The company recovers the high-purity carbon dioxide produced by the purification of tail gas, which is applied to many fields such as food, metallurgy, tobacco, agriculture, the chemical industry, and electronics. Currently, Kaimet Gas has nine subsidiaries in Yueyang, Huizhou, and other places. The production of high-purity carbon dioxide in 2020 will be

460,000 tons. The technical level was relatively high, and it is necessary and feasible to expand the scale further. The technical efficiency scores of Hangguo and Sunresin New Materials were the lowest, at only 0.045 and 0.056, respectively. These two companies have been at the bottom in terms of technical efficiency in recent years, and the problem of low TIE is more severe and should be adjusted in time. In addition, the pure technical efficiency of Binglun Environment, Hangzhou Oxygen Plant Group, Haohua Chemical Science and Technology, and Huaguang Huanneng reached 1, indicating that these four companies' low technical efficiency value was mainly affected by scale efficiency. The common scale efficiency of Hangzhou Oxygen Plant Group was primarily due to the contraction of the equipment business in recent years because of downstream fluctuations such as those in the steel and chemical industries. This also indicated that the industry and policies greatly influence the carbon capture industry. Since the independent research and development of the first lithium bromide refrigerator, Shuangliang Eco-energy Systems has provided society with more than 30,000 energy-saving devices, which is equivalent to building 25 fewer 600-megawatt thermal power plants and reducing carbon dioxide emissions by 100 million tons per year. In addition, 27 hectares of forest will be rebuilt, saving 2.83 billion m^3/year of water. However, there is still room for further improvement in its market size. Energy-saving equipment is still one of the essential development directions in the field of carbon capture.

4.2. Dynamic Analysis

4.2.1. Year Perspective

In Table 7, we notice that the average TFP of the 10 listed companies from 2018 to 2021 was 0.930, a decrease of 7%. The average change in technical efficiency was 1.618, and the technical efficiency increased by 61.8%. Among them, the average change in pure technical efficiency was 1.302, an increase of 30.2%; the average change in scale efficiency was 1.243, an increase of 24.3%. The average technological progress was 0.575, down 42.5%. From the table, we can conclude that the decline in the TFP of the listed companies was mainly affected by technological progress, indicating that the lag in technological progress has led to the decline in TFP. From a vertical perspective, the TFPs in 2019–2020 and 2020–2021 were both greater than 1, and the growth rates were relatively large, reaching 12.2% and 2.6%, respectively, of which technological progress had the greater impact, increasing by 18%, 4%, and 24.3%, respective to each period. Through the analysis of each period, especially in 2018–2019, the technical efficiency increased by 430.93%, and the pure technical efficiency and scale efficiency increased by more than 100%. However, because of the decrease of 87.1% in technological progress, the TFP decreased by 30.3%. This suggested that the changing trend of technological progress was consistent with the changing trend of TFP, and the annual change of TFP was mainly affected by changes in technological progress.

Table 7. Corporate Malmquist Index and its Decomposition Index.

Year	Effch	Techch	Pech	Sech	Tfpch
2018–2019	5.393	0.129	2.465	2.188	0.697
2019–2020	0.952	1.18	0.97	0.981	1.122
2020–2021	0.826	1.243	0.922	0.895	1.026
Mean	1.618	0.575	1.302	1.243	0.93

4.2.2. Enterprise Perspective

As shown in Table 8, to analyze each enterprise more clearly, this paper classified 10 enterprises according to the measurement results, which were divided into solid growth type (TFP $\geq$ 1.1), weak growth type (1$\leq$ TFP < 1.1), and soft reduction type. Type (0.9 $\leq$ TFP < 1) and strong reduction type (TFP < 0.9) were four categories. There were two strong growth enterprises, Binglun Environment and Hunan Kaimeite Gases. Hunan Kaimeite Gases had the highest TFP, reaching 1.493, an increase of 49.3%. Both technical efficiency and technological progress were improved, and the increase in technological progress was 128%. The improvement of KMT gas TFP was mainly affected by technical efficiency. Likewise, Moon Environment Technology was also primarily affected by technical efficiency. The technological progress of all enterprises was relatively low, indicating that it was the key to further improvement of TFP. There were two weak growth enterprises, Haohua Chemical Science and Technology and Shuangliang Eco-energy Systems. The improvement of Haohua Chemical Science and Technology and Shuangliang Eco-energy Systems was mainly affected by the advance in pure technical efficiency. Still, their technological progress also declined significantly. Weak reduction enterprises included Hangzhou Oxygen Plant Group, Hangguo, and Sunresin New Materials. It can be seen from the analysis that the decline in TFP of these three enterprises was mainly caused by technological progress. Increasing the research and development of enterprise technology should be their focus. There were three strong reduction enterprises, SPIC Yuanda Environmental-Protection, Wuxi Huaguang Environment and Energy Group, and Guanghui Energy. Among them, Guanghui Energy saw a decline in TFP because of technological progress and technical efficiency. The technical efficiency of SPIC Yuanda Environmental-Protection and Huaguang Huaneng Energy increased significantly. The slow progress of technology leads to the decline in the production efficiency of enterprises. Therefore, promoting the research and development of new technologies should be the main development direction in the future. It is worth noting that Guanghui Energy had the most significant decline among the 10 companies, with a decrease of 63.5%, and technological progress also dropped by 56.3%. As a resource-based enterprise, Guanghui Energy mainly relies on the sales of resources for its business and has not invested much in carbon capture technology.

Table 8. Malmquist Index of Enterprise Technology Innovation and Its Decomposition Index.

Firm	Effch	Techch	Pech	Sech	Tfpch
Moon Environment Technology Co., Ltd.	2.05	0.56	1.81	1.133	1.148
Hangzhou Oxygen Plant Group Co., Ltd.	1.787	0.541	1	1.787	0.967
Xizi Clean Energy Equipment Manufacturing Co., Ltd.	1.77	0.56	1.744	1.015	0.991
Hunan Kaimeite Gases Co., Ltd.	2.28	0.655	1.267	1.8	1.493
Sunresin New Materials Co., Ltd.	1.886	0.512	1.306	1.444	0.966
SPIC Yuanda Environmental-Protection Co., Ltd.	1.498	0.571	1.424	1.052	0.855
Haohua Chemical Science and Technology Corp., Ltd.	1.486	0.708	1.409	1.054	1.053
Wuxi Huaguang Environment and Energy Group Co., Ltd.	1.457	0.597	1	1.457	0.869
Shuangliang Eco-energy Systems Co., Ltd.	1.63	0.653	1.55	1.052	1.064
Guanghui Energy Co., Ltd.	0.835	0.437	0.86	0.97	0.365
Mean	1.618	0.575	1.302	1.243	0.93

5. Discussion

First, the specific CCUS implementation path should be determined according to locally suitable geological conditions. The capture of carbon dioxide is the first stage of CCUS technology and the most critical process in the development of CCUS. The premise of developing CCUS technology is to have a sufficient "carbon source" guarantee, and carbon capture is crucial to obtaining a high-quality and abundant "carbon source." Currently, CCUS projects at home and abroad are based on carbon capture as a carrier, relying on efficient capture technology to export usable "carbon products." From the perspective of coverage technology, China's carbon dioxide capture sources currently cover various technologies such as pre-combustion, post-combustion, and oxy-fuel combustion capture in coal-fired power plants. Suitable emission sources include power plants, steel plants, cement plants, smelters, chemical fertilizers, synthetic fuel plants, and hydrogen production plants based on fossil raw materials, among which fossil fuel power plants are the most important source of carbon dioxide capture. Among the three carbon collection technologies, the two technologies of post-combustion separation and pre-combustion separation are relatively mature, and oxy-fuel combustion is still in the demonstration stage. The application of carbon capture technology is mainly concentrated in the oil and gas, coal, and power industries.

Second, various mechanisms should be established to coordinate with multiple departments to pave the way for the orderly implementation of CCUS. Accelerating the research and development of carbon emission futures products and promoting the construction of a green and low-carbon economic system with a market-oriented mechanism is of great significance for the realization of “improving the market trading system of futures and spot linkages and enhancing the price influence of carbon emission rights.” Through the collective participation of many factors and means, such as TI, infrastructure construction, and the transformation of investment and financing models and behaviors, the market mechanism is used to tap the market value of the carbon emission reduction industry, and the formation of a unified carbon price in the market can help guide capital flow, to encourage more enterprises to actively participate in the development and innovation of carbon emission reduction technologies, to accelerate the emission reduction process and achieve the strategic goal of carbon neutrality.

Third, the government should accelerate the establishment of the CCUS legal framework. On the basis of improving the existing policies, policies and regulations for the trial implementation of CCUS-related industries should be formulated, such as the method of sealing and selecting land, development and utilization plan templates, ledger management system, ecological compensation methods and standards, ecological environment monitoring goals, environmental governance tasks and financial guarantee, early risk warning mechanism, emergency accident handling plan, and safety accident responsibility identification and accountability, etc. On the one hand, it provides constraints and a basis for project construction and operation, and on the other hand, it gives the basic experience that enables the legal development of CCUS technology. Through social group standards, local standards, and industry standards, enterprises can improve the CO_2 capture method, capture purity, utilization method, pipe network design, and pipeline transportation volume. There will be laws to obey regarding storage site selection and sealing techniques, and national standards for the development of CCUS technology.

6. Conclusions

This study enriches the evaluation of the policy and the TIE of listed companies in China. There are numerous studies on the importance of CCUS and firm innovation, and most of them affirm the government’s positive effect on CCUS. Researchers have also analyzed government funding as an indispensable part of firms’ innovation in CCUS. However, few scholars have studied the relationship between CCUS and corporate profitability. Fewer studies have investigated the extent to which the use of technology can improve the business’s profitability. This study bolsters the empirical evidence that advances in CCUS are helping companies capture more market share and make more profits. It makes recommendations commensurate with the dual-carbon strategy and aims to foster innovation in CCUS, which will be a favorable reference for firms seeking ecological sustainability and economic win-win. The limitation of this paper is that it did not analyze and summarize the factors affecting the TIE of enterprises in order to carry out correlation detection on the TIE value of relevant listed companies and to deeply explore the factors influencing the TIE of enterprises. The future research direction will be to study and analyze the problems of personnel input and environmental input, TI input, profitability and total profit output, and environmental issues such as enterprise scale and capital structure.

The development of domestic CCUS projects is still in the stage of technology accumulation. For innovative companies, although domestic CCUS must be improved in terms of policies, systems, funds, and projects, the number of existing players and the competition pressure are small. For potential entrants or investment institutions on the track, the CCUS track is not crowded, there is no leading enterprise, and it is still a wide open field. Some CCUS technologies in China have been commercialized. In terms of scale, China already has the engineering capacity to capture, utilize, and store carbon dioxide on a large scale and is actively raising the CCUS industrial cluster of the whole process. CCUS is an indispensable technology option for carbon-neutral transition, which requires policy incentives, and it has joined forces with enterprises to accelerate the promotion. In China's future CCUS ecosystem, all parties should work together and continue to calibrate suitable policies for China's cost-effective implementation path to promote the large-scale implementation of CCUS.

Finally, it is necessary to establish a CCUS ecosystem of cross-industry and cross-border cooperation, so that policy makers and enterprises can have effective dialogues, unite all parties, pool resources, and achieve synergies. It can actively cooperate and exchange with relevant departments and enterprises in Europe and the United States to jointly promote the cost reduction in CCUS and the realization of carbon neutrality goals. Enterprises must pay close attention to the relevant policy trends and technological progress of CCUS within the policy framework, actively explore new business models for carbon dioxide utilization, and seize opportunities one step ahead of others in the general trend of carbon-neutral transformation. Ample power and oil and gas enterprises with a specific capital base should actively carry out CCUS pilot projects with universities and scientific research units and strive to become world-class CCUS service providers.

Author Contributions: Conceptualization, X.X.; methodology, X.C.; software, Y.Z.; validation, T.W. and D.H.; formal analysis, D.H.; investigation, X.C.; resources, X.X.; data curation, T.W.; writing—original draft preparation, D.H.; writing—review and editing, X.X. and X.C.; visualization, Y.Z.; supervision, Y.Z.; project administration, X.X.; funding acquisition, T.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Major Projects of National Social Science Fund, grant number 20&ZD205; the Projects of National Social Science Fund, grant number 19CFX052; Research project of State Intellectual Property Office of China, grant number SS21-B-015; The National Natural Science Foundation of China, grant number 71974144; The fund of the Key Laboratory of Cities' Mitigation and Adaptation to Climate Change in Shanghai, grant number QHBHSYS201906.

Data Availability Statement: Data is contained within the article. Further requests can made to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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