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From Carbon Capture to Cash:
Strategic Environmental Leadership, AI, and the Performance of U.S. Firms

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ABSTRACT

This research unravels the strategic confluence of environmental leadership and cutting-edge Artificial Intelligence (AI) in the realm of Carbon Capture technology, and their combined effect on the financial fortitude of U.S. firms. It posits that a firm's environmental vision, when led by transformative green leadership, significantly propels the effective adoption of Carbon Capture solutions. Drawing on data from 145 publicly traded U.S. entities from the years 2017 to 2019, provided by the Carbon Disclosure Project and Compustat, this study meticulously explores the interrelation between a firm's environmental initiatives - including managerial focus, shared vision, proactive green strategies, and innovation—and its performance outcomes. The findings illuminate that while environmental commitments like management focus and a unified vision greatly encourage the embracement of Carbon Capture, the financial implications of these adoptions present a complex picture.

KEYWORDS

Carbon Capture, Artificial Intelligence, Strategic Environmental Leadership, Firm Performance, Sustainable Innovation, U.S. Market

INTRODUCTION

As the urgency to combat climate change intensifies, implementing carbon capture and storage (CCS) has become increasingly critical in climate stabilization and achieving net-zero targets. Recognizing the role of CCS in reducing carbon emissions, several countries are proactively encouraging the adoption of CCS technologies by companies (Ekemezie & Digitemie, 2024; Tarim et al., 2021; Verbeke et al., 2017; Johnson et al., 2015). Norway's Snøhvit project, for instance, aims to capture nearly one million tons of CO_2 emissions annually, sequestering it in the saline formations of the Snøhvit field (Estublier & Lackner, 2009). Some countries like the United States, Australia, the United Kingdom, and Sweden are all actively participating in and advancing the implementation of CCS (Roos Radevski & Zhao, 2024; Lu et al., 2011; Cook, 2009; Benson & Surles, 2006).

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While pilot and demonstration projects for CCS are progressing globally, the widespread adoption of this technology by firms remains limited due to its high costs (Kang et al., 2021). The expense of generating electricity from coal-fired power plants with CCS hinges on the chosen capture technology and the CO_2 concentration at the source (Rolfe et al., 2018). Over 75% of the total CCS costs can be attributed to capture and compression processes, with the remainder allocated to transportation and underground storage (Roussanaly et al., 2021; Oh, 2010). Pipeline transportation costs are influenced by economies of scale and the pipeline length at each site. Additionally, the "energy penalty" incurred during the capture and compression processes is a significant factor to consider (Yadav & Mondal, 2022).

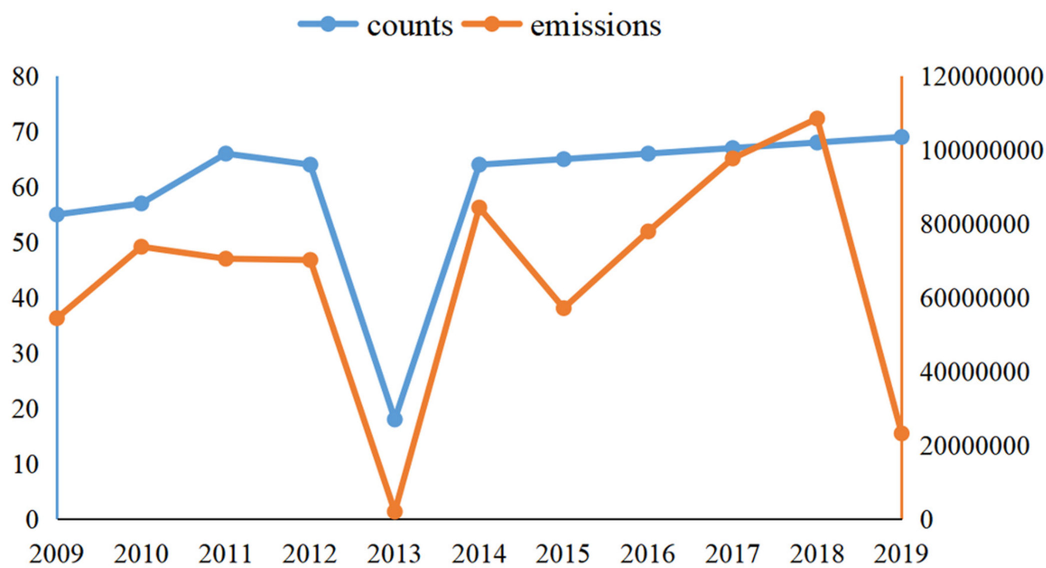
To reduce these costs, academic researchers are increasingly turning to AI technologies. AI's potential in optimizing CCS processes is gaining recognition, with recent studies highlighting its efficacy (Al-Sakkari et al., 2024). Priya et al. (2023) demonstrated that through rapidly processing and interpreting complex data, AI can significantly reduce computation times in CO_2 capture processes. By deploying AI for real-time analysis of extensive data sets, efficiency in CO_2 capture can be significantly improved, thus lowering overall costs. However, AI can not only enable more efficient decision-making in CCS operations to reduce operational expenses and energy requirements but also improve the acceptance of CCS. As a novel carbon emission reduction technology, CCS faces unique institutional challenges and debates over its legitimacy (Latif et al., 2024). Firms considering CCS must weigh not only the technological costs but also public perception (Fikru & Nguyen, 2024). Gaining public and private support through sponsorship of research and development programs is essential for the widespread implementation of CCS (Griffiths et al., 2005). Consequently, firms employing CCS can leverage these technologies to demonstrate their commitment to emission reduction, thereby aligning with social legitimacy criteria and appealing to stakeholders and external investors (Godfrey, 2005). The integration of AI in CCS not only addresses operational challenges but also potentially enhances the technology's acceptance and perceived legitimacy by showcasing cutting-edge, efficient solutions to environmental concerns.

In the current business landscape, corporate strategy and behavior are increasingly evaluated based on economic outcomes and environmental impact. The natural-resource-based view (NRBV) posits that a firm's resources and environmental capabilities can significantly shape its interaction with the environment, thereby offering competitive advantages (Lau & Wong, 2024; Mishra & Yadav, 2021; Albertini, 2019). This paper argues that a firm's environmental capabilities—encompassing management attention, shared vision, proactive environmental strategies, and continuous innovation—directly influence the adoption, scaling, and effective use of CCS. Additionally, it is proposed that these environmental capabilities, in conjunction with CCS, are positively correlated with firm performance, as measured by return on assets (ROA). This investigation is conducted using secondary data obtained from the Carbon Disclosure Project (CDP) questionnaire, focusing on a sample of 145 U.S.-listed firms from 2017 to 2019 (Lopez & Rotaru, 2024; Ning & Khuntia, 2023).

The contributions of this study are threefold. Firstly, it quantifies the environmental capabilities of firms, comprising various resources, and conducts a quantitative empirical examination of NRBV across four dimensions: management attention, shared vision, environmental strategy proactivity, and continuous innovation. Secondly, the study identifies and analyzes the factors within environmental capabilities that influence a firm's implementation of CCS, providing insights into the economic ramifications of CCS adoption, particularly their impact on ROA. Finally, the research uncovers that *intelligentization* serves as a pathway through which CCS influences a firm's financial performance, thereby offering empirical support for the application of AI in corporate settings.

The remainder of this study is organized as follows. The second section contains the status of CCS and its theoretical background. The third section provides the research hypotheses. The fourth section provides the data and methodology. The fifth section reports the regression results. The sixth section provides a discussion of the results and implications. The seventh section presents the conclusion.

Figure 1. Amount of CO_2 storage and the number of firms using CCS in the United States, 2009–2019 (Unit: Tons CO_2)



Note. Compiled by the authors according to CDP 2009–2019.

STATUS OF CARBON CAPTURE AND STORAGE AND THEORETICAL BACKGROUND

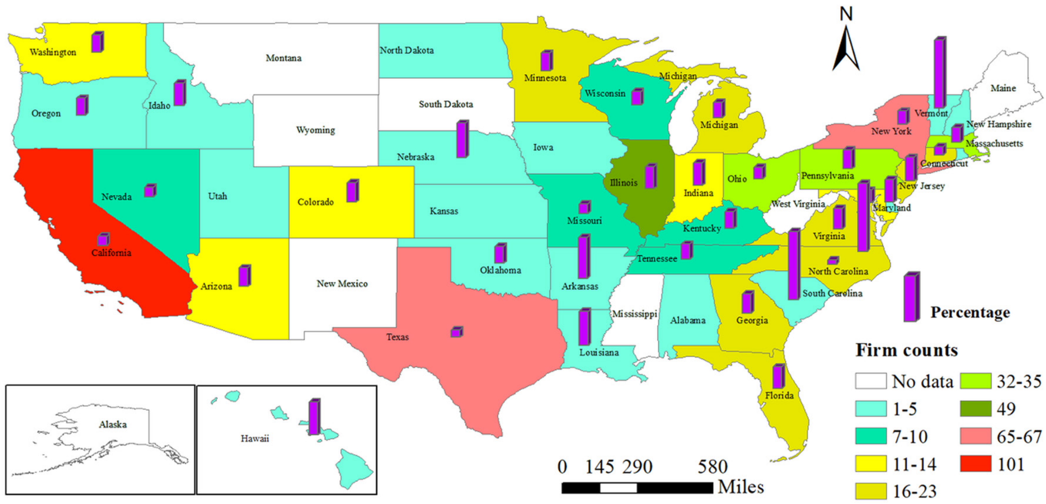
Status of Carbon Capture and Storage

CO_2 capture with deep underground storage is currently the most advanced CCS technology, with the greatest prospect for large-scale development in the coming decades (Benson & Surles, 2006). The number of firms using CCS to reduce CO_2 emissions has risen since 2009. The statistics from CDP indicate that—as illustrated in Figure 1—the total number of firms using CCS increased from 55 in 2009 to 69 in 2019. The emissions from biologically sequestered carbon also increased from 54,418,148 metric tons in 2009 to 108,504,422.5 in 2018. However, there was a significant decrease in 2019; the reason may be the impact of COVID-19 (Guérin & Suntheim, 2021). The shutdown in economic activity precipitated by COVID-19 resulted in a temporary decline in global carbon emissions. Although the number of firms increased, the low carbon output resulted in a low sequestered carbon volume.

AI has revolutionized CCS technology (Derrick, 2024). Some of the key technologies in CCS now require the support of AI. For example, AI can help us to innovate and expedite the solubility trapping process. Existing scholars have developed energy-efficient solvents for CO_2 capture, which enables higher efficiency and storage capacity in CCS applications. Besides this, others have focused on improving algorithms, using AI to cut the time and cost of modeling CCS methods. They apply these algorithms to CCS in typically hard-to-decarbonize industries to help firms achieve carbon reduction.

Figure 2 presents data on the prevalence of CCS usage among firms in various American states from 2009 to 2019. The data reveals an average adoption rate of 26.4% across the board. A closer examination of the figure shows a notably high adoption rate in South Carolina, Vermont, Hawaii, and Washington, D.C., each registering a 100% adoption rate, as depicted by the purple bar graphs in Figure 2. This statistic is somewhat misleading, as it results from the fact that in each of these states, only one firm was surveyed, and that firm was utilizing CCS. Setting aside these outliers, the adoption rate of CCS in most other states remains relatively low. For example, in California, home

Figure 2. Number of firms using CCS in American States from 2009–2019



Note. Compiled by the authors according to CDP 2009–2019.

to the largest number of surveyed firms, the adoption rate was 13.9%. Similarly, in Texas, which also boasts a significant number of firms, the rate is 10.8%. These figures suggest that most firms in the United States have yet to embrace CCS technology as an effective means of reducing CO_2 emissions.

Theoretical Background

The traditional resource-based view (RBV) highlights the relationship between a firm's internal resources and capabilities and its sustained competitive advantages, as noted by Ray et al. (2004). However, this perspective overlooks the environmental implications of a firm's activities. Addressing this shortfall, Hart (1995) proposed the NRBV, which emphasizes developing firm-specific competitive advantages through strategic interaction with the natural environment. NRBV extends RBV's principles, focusing on the positive, environmentally beneficial impact of resources and their role in sustaining a firm's operations, as discussed in various studies (Andersén, 2021; McDougall et al., 2019; Marshall et al., 2015; Johnsen et al., 2014; Chicksand et al., 2012). Scholars argue that competitiveness stems from effectively utilizing the right resources (Yu et al., 2017; Yusuf et al., 2017; Hitt et al., 2016). Recent research has begun exploring the influence of a firm's environmental resources and capabilities on its overall performance, particularly how environmental strategies correlate with this. Given the impact of NRBV resources, firms exhibit diverse environmental practices (Nishant et al., 2016). Extensive studies have been conducted on factors like shared vision, environmental strategy proactivity, continuous innovation, organizational learning, and cross-functional coordination in the context of environmental capabilities (Yang et al., 2019; Ketprapakorn & Kantabutra, 2019; Suarez-Perales et al., 2017; Journeault, 2016; Alt et al., 2015).

This paper argues that NRBV is a valuable theoretical framework for understanding the adoption of CCS for organizational capabilities and pollution prevention. It also proposes that management attention reflects environmental capabilities. CCS offers high-carbon corporations technologies for negative emissions and significant reductions in industrial processes (Zapantis et al., 2019). With an increasing awareness of CCS technologies as a climate change mitigation strategy, there is a noticeable shift in managerial attention toward implementing CCS (Ocasio, 2011). The role of CEOs, especially founder CEOs, is pivotal in this context. Founder CEOs, typically more concerned with reputation and long-term performance, are less likely to engage in environmental violations and more inclined toward growth strategies (Abebe & Acharya, 2022; Souder et al., 2012). Additionally, the board of directors, particularly independent directors, plays a significant role in steering attention toward emissions control projects and recognizing the long-term investment value in environmental issues (Ammer et al., 2020; Liao et al., 2015). Therefore, this study uses the presence of independent directors and founder CEOs as proxies for management attention.

This research examines the influence of environmental capabilities on firms implementing CCS, focusing on four aspects: management attention, shared vision, environmental strategy proactivity, and continuous innovation. As a proactive environmental strategy, the implementation of CCS is shaped by environmental capabilities and, in turn, impacts firm performance. Višković et al. (2014) note that the primary challenge with CCS technology is the associated high costs and resulting financial pressure on firms. The competitiveness of firms using CCS varies with the price of CO_2 allowances. When this price exceeds \$28/t CO_2, firms implementing CCS observe a higher internal rate of return (Bassano et al., 2014). Furthermore, the study examines the effects of environmental capabilities on firm performance. Management attention is crucial in selecting strategies that enhance financial outcomes. Shared vision fosters continuous motivation and development, creating clear competitive advantages and high performance (Adnan & Valliappan, 2019). González-Benito and González-Benito (2005) identified four dimensions of environmental strategy proactivity (internal production processes, product design attributes, logistics processes, and planning and organization practices), underlining its positive impact on business performance. Lastly, continuous innovation is key to achieving competitive advantage and improving firm performance through enhanced productivity and efficiency.

Given the limited empirical research in this area, this paper seeks to deepen understanding of the interplay between CCS, environmental capabilities, and financial outcomes. It adopts a multi-dimensional approach based on NRBV, focusing on management attention, shared vision, environmental strategy proactivity, and continuous innovation.

HYPOTHESIS DEVELOPMENT

Environmental Capabilities and Carbon Capture and Storage

The influence of management on environmental issues is significant and unavoidable. As part of the commitment to sustainable development, many firms are increasingly adopting greener strategic orientations. Green transformational leadership is pivotal in this context, playing a vital role in bolstering a firm's environmental performance (Riva et al., 2021; Singh et al., 2020; Li et al., 2020). Such leadership focuses managerial attention on environmental stewardship, reflecting a commitment to rigorous environmental protection standards. Under this leadership style, managers actively encourage their teams to align with and achieve the firm's environmental objectives (Chen et al., 2014). Additionally, green transformational leaders often possess a broader vision concerning environmental issues, which can enhance the development and performance of green products (Jia et al., 2018). Given that managerial attention is a finite resource, allocating this attention can result in diverse strategic trajectories (Shepherd et al., 2017). It is posited that when managerial focus is directed toward environmental strategies, adopting carbon emission reduction technologies, such as CCS, becomes more feasible and likely. This leads to the formulation of the following hypothesis:

Hypothesis 1A (H1A): Managerial attention toward environmental capabilities positively correlates with adopting CCS technology.

A shared vision acts as a structural and strategic resource within an organization, integrating and guiding the actions of its members (Carton et al., 2014). When a firm cultivates a strong shared vision, its members typically exhibit a unified sense of purpose, aligning their efforts with agreed-upon objectives and a consistent strategic direction (Sosik & Dinger, 2007). This alignment fosters intellectual and affective commitment toward achieving strategic goals and engenders a heightened sense of responsibility for the firm's development. Given that employees play a critical role in executing a firm's emission reduction initiatives, their collective environmental consciousness is essential for the firm's sustainable practices (Markey et al., 2019). Research has demonstrated that employee contributions, in terms of knowledge and ideas, are invaluable to environmental management (Ikram et al., 2019; Paillé et al., 2014). A shared vision not only motivates employees to adopt new technologies, practices, and strategies but also aligns their aspirations with the firm's goals in carbon emission reduction (Eldor & Harpaz, 2019). When employees and the firm share a common commitment to carbon emission reduction measures, the firm is more likely to implement such technologies successfully. Based on these considerations, the following hypothesis is proposed:

Hypothesis 1B (H1B): A shared vision focused on environmental capabilities significantly and positively influences a firm's implementation of CCS technologies.

The landscape of environmental regulation is evolving, with an increasing emphasis each year. In response, numerous firms are integrating environmental initiatives into their business strategies. The approach to climate change within the corporate sector has transitioned from passive to proactive engagement (Graham & Potte, 2015). The decision to adopt a proactive environmental strategy hinges on a firm's willingness to commit substantial financial and managerial resources over the long term. Such proactivity demands an ongoing dedication to seeking new opportunities and environmental innovations (Elijido-Ten, 2017). By adopting a proactive stance toward environmental strategy, firms not only heighten their focus on environmental competitiveness but also build the necessary resources and capabilities to support these endeavors. However, the benefits of proactive environmental strategies are not uniform across all firms (Hart, 1995). A true competitive advantage is achieved when a chosen strategy is well-supported by adequate resources and capabilities (Barney & Arikan, 2001; Clarkson et al., 2011). This leads to the development of the following hypothesis:

Hypothesis 1C (H1C): A firm's proactivity in environmental strategy, as a component of its environmental capabilities, is positively correlated with the adoption and effective use of CCS technology.

Innovation is fundamentally linked to the accumulation of knowledge and the progression of learning processes (Colombelli & von Tunzelmann, 2011). Firms that consistently innovate can carve out competitive advantages, as both past and present innovations lay the groundwork for future inventive endeavors. Firms engaged in continuous innovation distinguish themselves from competitors through a more substantial accumulation of knowledge and a robust capacity for innovation. Such firms leverage their innovative activities to create competitive advantages, often at lower costs (Tavassoli & Karlsson, 2015). Innovation often emerges from recombining existing ideas in novel ways, implying that the larger a firm's repository of pre-existing knowledge and ideas, the greater its capability to recombine these elements to generate new concepts and insights (Weitzman, 1998). Based on these insights, the following hypothesis is proposed:

Hypothesis 1D (H1D): The commitment to continuous innovation within a firm's environmental capabilities is positively associated with the adoption and utilization of CCS technologies.

Financial Impact of Carbon Capture and Storage and Environmental Capabilities

According to the NRBV of firms, attaining competitive advantages through environmentally sustainable activities yields positive economic returns. Environmental capabilities play a crucial role in forging this link. Firms must orchestrate a complex coordination of human and technical resources to effectively address environmental challenges (Brammer et al., 2012). A managerial commitment to environmental responsibility fosters the establishment of pro-environmental objectives, which is instrumental in advancing both technological and managerial aspects of environmental change (Al-Swidi et al., 2021). Technological advancements not only confer competitive advantages but also bolster financial performance. A shared vision within a firm cultivates common values and goals, motivating employees to surpass performance expectations (Chang et al., 2019). When management and employees are united in their vision toward environmental issues, they are more likely to pursue effective carbon emission reduction strategies, thereby enhancing firm performance (Chang et al., 2020; Chen et al., 2014; Hofhuis et al., 2018). Proactive environmental strategies have been recognized for fostering a positive correlation between environmental initiatives and economic outcomes (Cañón-de-Francia & Garcés-Ayerbe, 2019; Trumpp et al., 2015). Studies by González-Benito and González-Benito (2005) and Aragón-Correa et al. (2008) suggested that firms engaged in proactive environmental practices experience a beneficial impact on their financial performance. Moreover, innovation is a key driver of firm performance (Nadkarni & Narayanan, 2007), with variations in innovation behavior reflecting differences in firm performance (Geroski et al., 1997). Persistent innovation facilitates the implementation of differentiation strategies, creating cumulative effects and core competitiveness. Firms that engage in continuous innovation tend to outperform those that innovate sporadically or not at all.

Legitimacy, derived from a firm's environmental performance, enhances stakeholder satisfaction and generates economic value (Yadav et al., 2017). As a low-carbon technology, CCS not only demonstrates a firm's commitment to environmental issues but also enhances its environmental reputation, thereby offsetting the costs associated with the technology. Environmental resources endow firms with a competitive edge, increasing profit margins and thus improving financial performance. In light of these considerations, the following hypotheses are proposed:

Hypothesis 2A (H2A): The integration of CCS and environmental capabilities positively correlates with financial performance.

Hypothesis 2B (H2B): The application of AI technology serves as a conduit through which CCS can enhance financial performance.

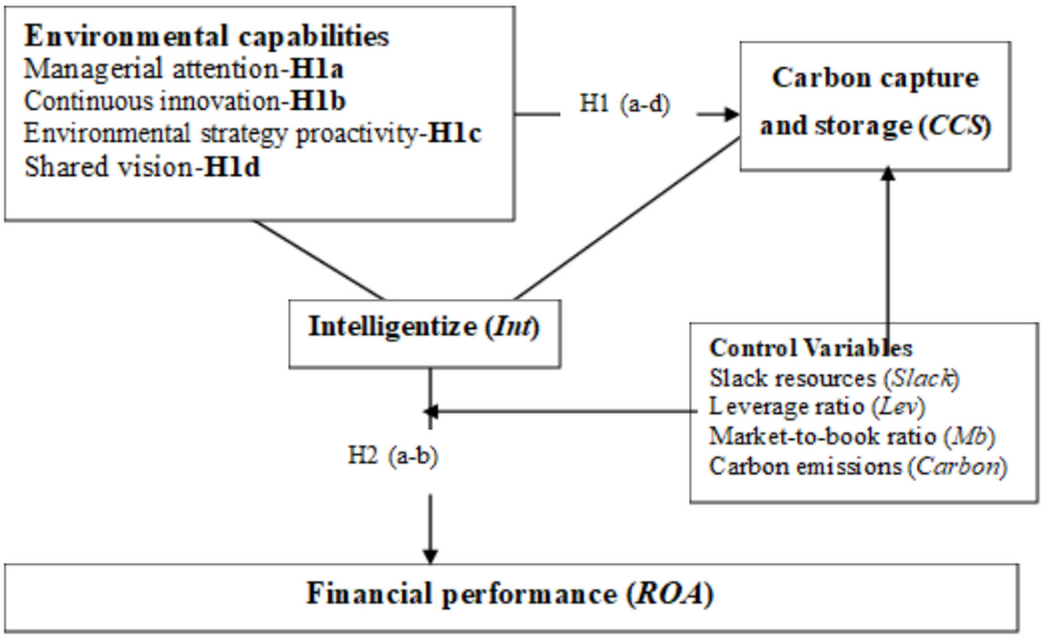
Figure 3 presents a summary of all hypothesized relationships. The selection of the variables constituting the relationships, including their sources in the CDP reports (refer to Table 1), is discussed next.

DATA AND METHODOLOGY

Data Collection

Understanding the factors influencing firms' decisions to implement CCS and assessing the outcomes of such implementations are challenging due to the absence of standardized measurement scales and objective, consistent measures. Their great variability across different firms compounds the complexity of assessing these factors. The data obtained from a third-party information service provider is invaluable in analyzing the factors affecting firms' CCS implementation based on voluntarily reported information on environmental capabilities. The primary source for this analysis is the 2017–2019 reports published by CDP, a UK non-profit organization established in 2000 aimed at collecting and disseminating climate change-related information voluntarily disclosed by firms (CDP, 2020). Supported by institutional investors, CDP had received responses from over 5500 firms worldwide by 2015. The GHG emission data collection process of CDP aligns with the protocol of the World Resource Institute (WRI) and is widely utilized in academic research (Caby et al.,

Figure 3. Research framework



2024; Bedi & Singh, 2024; Ning et al., 2019). Kolk et al. (2008) suggested that the CDP database is increasingly reliable.

CDP reports provide emissions information, including firms' biologically sequestered carbon and CCS, for several U.S.-listed firms. The sample for this study comprises firms listed from 2017–2019 that shared CCS information with CDP. In 2017, CCS information was available for 73 firms, accounting for 13.2% of the listed firms. In 2018, the figure was 74 firms (8.5% of the total), and in 2019, 65 firms (7.2% of the total). Firms reporting zero CCS emissions were excluded, as this does not reflect the impact of firm factors on actual CCS emissions. According to CDP reports, the number of firms with zero CCS emissions was 1, 2, and 3 in 2017, 2018, and 2019, respectively. After removing these firms, the sample consisted of 206 firms across thirteen sectors. Each firm's ticker symbol on the American Stock Exchange was identified based on its name. From the initial list, 168 firms with ticker symbols were retained. After matching data with CDP reports and the Compustat database and removing firms with incomplete or missing financial data, the final sample size was 145 firms.

It is posited that the factors in the CDP report used to measure firms' environmental capabilities exert influence before the observation year, enhancing the explanatory variables' usefulness. *CCS* in tons of CO_2 and *ROA* are the dependent variables, with *ROA* defined as operating income before depreciation divided by total assets. Eight independent variables encompassing four dimensions of environmental capabilities were used, with two firm-related factors measuring each dimension. In the management attention dimension, the willingness to implement sustainable development technology (CCS) was gauged by the number of independent directors (*Independent*) and CEO founder status (*Founder*). For shared vision, the collective low-carbon consciousness of firm leaders and employees was assessed through leadership vision (*Boardv*) and total employee vision (*Empv*). The environmental strategy proactivity dimension was measured using climate change risks and opportunities (*Oppo*) and emission reduction methods (*Strategy*). Continuous innovation was evaluated by participation in emissions trading schemes (*Ets*) and the proportion of low-carbon revenue (*Lowpro*). Additionally, *Intelligentize* (*Int*) was chosen as a mediating variable, measured by the number of methods firms use to reduce emissions.

Control variables included the firm's financial characteristics and emission levels. Slack resources (*Slack*) were calculated as the ratio of current assets to current liabilities. The leverage ratio (*Lev*) was defined as the sum of long-term debt and current liabilities divided by total assets. The market-to-book ratio (*Mb*) was the ratio of the market value of equity (price times shares outstanding) over the book value of equity. Carbon emissions (*Carbon*) represented Gross Global Scope 1 emissions. Detailed definitions of these variables are provided in Table 1.

Descriptive Statistics

The hypotheses were evaluated using regression analysis, with CCS and the natural logarithm of ROA serving as dependent variables. This approach was employed to establish the model's empirical validity, illustrated in Figure 3. Variance inflation factor (VIF) tests were conducted to assess the potential for multi-collinearity. The results indicated that the highest VIF value was 1.45, significantly below the commonly accepted threshold of 10, suggesting a minimal risk of multi-collinearity among the independent variables. This finding supports the conclusion that multi-collinearity does not adversely impact the analysis. Table 2 displays the descriptive statistics and correlations among all variables included in the study. Below the main diagonal of the table, Pearson correlation coefficients are presented, while above the main diagonal, Spearman rank correlation coefficients are provided.

Regression Models

To ascertain the appropriate analysis model, the study employed Hausman's (1978) test for model selection. The outcome of this test yielded a *p*-value of 0.0141, which falls below the significance threshold of 0.05. Consequently, the fixed effect model was chosen based on its ability to analyze the contemporaneous correlation between regression variables and error terms. The relationship between CCS and environmental capabilities was then examined through the following regression analysis:

$$\begin{aligned} CCS_{i,t} = {} & \beta_0 + \beta_1 Independence_{i,t} + \beta_2 Founder_{i,t} + \beta_3 Boardexm + \beta_4 Empv_{i,t} \\ & + \beta_5 Oppo_{i,t} + \beta_6 Strategy + \beta_7 Ets_{i,t} + \beta_8 Lowpro_{i,t} + \beta_9 Int_{i.t} + \beta_{10} Slack_{i.t} \\ & + \beta_{11} Leverage_{i.t} + \beta_{12} Mb_{i.t} + \beta_{13} Carbon_{i.t} + \alpha_i + \delta_t + \varepsilon_{i,t} \end{aligned} \tag{1}$$

where *i* is the firm, and *t* is the year; $Independent_{i,t}$ is the number of independent directors; $Founder_{i,t}$ is whether the CEO is the founder; $Boardv_{i,t}$ is leadership vision; $Empv_{i,t}$ is total employee vision; $Oppo_{i,t}$ is climate change opportunity; $Strategy_{i,t}$ is emission reduction methods; $Ets_{i,t}$ is emissions trading schemes; $Lowpro_{i,t}$ is low-carbon revenue; $Int_{i,t}$ is Intelligentize; $Slack_{i,t}$ is slack resources; $Lev_{i,t}$ is leverage ratio; $Mb_{i,t}$ is market-to-book ratio; $Carbon_{i,t}$ is carbon emissions; α_i is firm fixed effects; δ_t is year fixed effects; β_0 is the intercept; $\varepsilon_{i,t}$ is the error term.

Moreover, the relationship between CCS, environmental capabilities, and ROA was tested. The estimation model is as follows:

$$\begin{aligned} ROA_{i,t} = {} & \beta_0 + \beta_1 CCS_{i,t} + \beta_2 Independence_{i,t} + \beta_3 Founder_{i,t} + \beta_4 Boardexm \\ & + \beta_5 Empv_{i,t} + \beta_6 Oppo_{i,t} + \beta_7 Strategy + \beta_8 Ets_{i,t} + \beta_9 Lowpro_{i,t} + \beta_9 Int_{i.t} \\ & + \beta_{10} Slack_{i.t} + \beta_{11} Leverage_{i.t} + \beta_{12} Mb_{i.t} + \beta_{13} Carbon_{i.t} + \alpha_i + \delta_t + \varepsilon_{i,t} \end{aligned} \tag{2}$$

where α_i is firm fixed effects, δ_t is year fixed effects, β_0 is the intercept, and $\varepsilon_{i,t}$ is the error term.

Further, the mediating effect test method was used to explore the influence path from CCS to ROA. The estimation model is as follows:

Table 1. Variable definition and measurement

Variable name	Question in the CDP questionnaire explanatory note or definition	Sign	Data source
ROA	The natural logarithm of operating income before depreciation/total assets		Compustat
CCS	Emissions from sequestered carbon relevant to the organization in tons CO_2	+	CDP
Managerial attention			
Independent directors (*Independent*)	The natural log of the total number of independent directors	-	Compustat
Founder CEO (*Founder*)	Whether the CEO is the founder of the firm (0 = no, 1 = yes)	+/-	Compustat
Shared vision			
Leadership vision (*Boardv*)	Do you have board-level monitoring of climate-related issues? (0 = no, 1 = yes)	+	CDP 2018 (Q1.1)
Total employee vision (*Empv*)	Do you provide incentives for managing climate change issues, including attaining targets? (0 = no, 1 = yes)	+	CDP 2018 (Q1.3)
Environmental strategy proactivity			
Climate change opportunity (*Oppo*)	Have you identified any climate change opportunities (current or future) that have the potential to generate a substantive change in your business operations, revenue or expenditure? (0 = no, 1 = yes)	+	CDP 2018 (Q2.4a)
Emission reduction methods (*Strategy*)	Do you integrate climate-related issues into business strategy? (0 = no, 1 = yes)	+	CDP 2018 (Q3.1)
Continuous innovation			
Emissions trading schemes (*Ets*)	Do you participate in any emissions trading schemes? (0 = no, 1 = yes)	-	CDP 2018 (Q11.1)
Low-carbon revenue (*Lowpro*)	What is the percentage of your green development revenue in total revenue?	-	CDP 2018 (Q4.5a)
Mediating variable			
Intelligentize (*Int*)	The natural logarithm of the number of methods used by firms to reducing emissions	+/-	Compustat
Control variables			
Slack resources (*Slack*)	The natural logarithm of current assets/current liabilities	+/-	Compustat
Leverage ratio (*Lev*)	The natural logarithm of long-term debt plus current liabilities/total assets	+/-	Compustat
Market-to-book ratio (*Mb*)	The natural logarithm of the price times shares outstanding/the book value of the equity	+/-	Compustat
Carbon emissions (*Carbon*)	What is your Gross Global Scope 1 emissions in tons CO_2e?	+/-	CDP 2018 (Q6.1)

$$\begin{aligned} Int_{i,t} = {} & \beta_0 + \beta_1 CCS_{i,t} + \beta_2 Independence_{i,t} + \beta_3 Founder_{i,t} + \beta_4 Boardexm \\ & + \beta_5 Empv_{i,t} + \beta_6 Oppo_{i,t} + \beta_7 Strategy + \beta_8 Ets_{i,t} + \beta_9 Lowpro_{i,t} \\ & + \beta_9 Slack_{i.t} + \beta_{10} Leverage_{i.t} + \beta_{11} Mb_{i.t} + \beta_{12} Carbon_{i.t} + \alpha_i + \delta_t + \varepsilon_{i,t} \end{aligned} \tag{3}$$

Where $Int_{i,t}$ is Intelligentize, α_i is firm fixed effects, δ_t is year fixed effects, β_0 is the intercept, and $\varepsilon_{i,t}$ is the error term.

Table 2. Descriptive statistics and correlation matrix

	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 *ROA*	-2.421	0.577	1	-0.179**	-0.073	0.049	-0.213**	-0.150*	-0.104	0.058	-0.127	-0.357***	-0.135	0.321***	0.105	0.823***	-0.448***
2 *CCS*	9.546	3.99	-0.154*	1	-0.005	0.073	0.086	-0.036	-0.127	-0.034	0.108	0.234***	-0.086	-0.149*	0.189**	-0.322***	0.647***
3 *Independent*	14.53	7.391	-0.068	0.003	1	0.013	0.035	0.243***	0.073	-0.022	0.058	-0.012	0.223***	-0.239***	-0.184**	0.074	0.08
4 *Founder*	0.018	0.133	0.056	0.061	-0.041	1	0.033	0.04	0.148*	0.024	0.114	-0.128	-0.053	0.106	-0.101	0.028	0.075
5 *Boardv*	0.958	0.2	-0.190**	0.092	0.026	0.033	1	0.320***	0.028	0.159*	0.155*	0.158*	0.243***	-0.244***	-0.151*	-0.134	0.204**
6 *Empv*	0.929	0.258	-0.153*	-0.052	0.186**	0.04	0.320***	1	0.103	0.287***	0.236***	0.083	0.252***	-0.278***	-0.098	-0.018	0.059
7 *Oppo*	0.512	0.501	-0.107	-0.107	0.029	0.148*	0.028	0.103	1	0.081	-0.059	0.021	-0.047	0.091	-0.123	0.074	-0.113
8 *Strategy*	0.976	0.153	0.029	-0.033	0.012	0.024	0.159*	0.287***	0.081	1	0.215***	0.05	0.127	0.092	-0.024	0.043	-0.092
9 *Ets*	0.613	0.488	-0.114	0.13	0.063	0.114	0.155*	0.236***	-0.059	0.215***	1	-0.017	0.306***	0.015	-0.092	-0.135	0.296***
10 *Lowpro*	23.16	44.63	-0.139*	0.143*	0.078	-0.076	0.116	0.049	0.013	-0.005	0.021	1	0.171**	-0.140*	0.076	-0.366***	0.208**
11 *Int*	1.403	0.516	-0.123	-0.098	0.251***	-0.048	0.233***	0.255***	-0.07	0.118	0.321***	0.154*	1	-0.143*	-0.023	-0.027	0.01
12 *Slack*	0.211	0.508	0.334***	-0.112	-0.140*	0.155*	-0.301***	-0.238***	0.105	0.082	0.006	-0.03	-0.162*	1	-0.233***	0.228***	-0.444***
13 *Lev*	-1.191	0.822	-0.039	0.189**	-0.019	-0.139*	-0.005	-0.072	-0.03	-0.042	0.039	0.087	0.119	-0.333***	1	0.006	0.134
14 *Mb*	0.642	0.498	0.792***	-0.303***	0.066	0.026	-0.175**	-0.016	0.064	0.05	-0.154*	-0.212**	-0.061	0.320***	-0.123	1	-0.445***
15 *Carbon*	13.35	2.477	-0.415***	0.623***	0.106	0.077	0.215***	0.053	-0.061	-0.103	0.307***	0.127	0.069	-0.423***	0.356***	-0.457***	1

Note. *CCS* is the natural log of CCS; *Independent* is the number of independent directors; *Founder* is whether the CEO is the founder of the firms; *Boardv* is leadership vision; *Empv* is total employee vision; *Oppo* is climate change opportunity; *Strategy* is emission reduction methods; *Ets* is the emissions trading scheme; *Lowpro* is low-carbon revenue; *Slack* is the natural log of slack resources; *Int* is the natural logarithm of the number of methods used by firms to reducing emissions; *Lev* is the natural log of leverage ratio; *Mb* is the natural log of market-to-book ratio; *Carbon* is the natural log of carbon emissions. Below the main diagonal is the Pearson correlation coefficient, and above the main diagonal is the Spearman rank correlation coefficient.

REGRESSION RESULTS AND ANALYSIS

Relationship Between Environmental Capabilities and CCS

The results from our analyses reveal the effect of environmental capabilities from four dimensions, as shown in Table 3. The estimated coefficient of *Independent* is -0.1549 and is marginally significant at the level of 0.01. The negative association between *Independent* and *CCS*, which is contrary to the proposed positive association, suggests that firms with a large number of independent directors cannot effectively promote the implementation of CCS. The estimated coefficient of *Founder* is -1.2405 and is marginally significant at the level of 0.01. The negative association between *Founder* and *CCS* indicates that when the CEO is also the founder, it has a negative effect on the implementation of CCS. New-venture and young companies, which are more likely to have retained their founding CEOs, generally have fewer resources to devote to CCS and like measures or are likely to have started fundamentally low-emission businesses.

The estimated coefficient of *Boardv* is 6.3303 and is marginally significant at the level of 0.01. The positive association between *Boardv* and *CCS* suggests that managers with environmental commitment promote the implementation of CCS. The estimated coefficient of *Empv* is -1.6707 and is marginally significant at the level of 0.1. The negative association between *Empv* and *CCS* suggests that employee commitment to the firm's environmental strategies does not affect the choice of CCS emission reduction technologies. The estimated coefficient of *Oppo* is 0.8625 and is significant at the level of 0.05, which indicates that climate change opportunities may induce firms to implement CCS technology. The estimated coefficient of *Strategy* is -2.4375 and is significant at the level of 0.05. Due to the high cost of CCS, firms will not choose to adopt CCS if other emission reduction strategies are available. *Ets* and *Lowpro* are insignificant to CCS, which indicates that a firm's capability of continuous innovation does not influence the implementation of CCS technology. Overall, if the four dimensions of environmental capabilities, three dimensions have an impact on a firm's implementation of CCS, indicating that environmental capabilities are a significant factor in efforts to the implement CCS technology. What's more, in the control variables, we find when firms possess a large amount of slack resources, they can facilitate the implementation of CCS. Firms with higher carbon emissions have a more urgent need for CCS technology, and intelligence supports the enthusiasm of these firms for CCS.

Impact of Carbon Capture and Storage and Environmental Capabilities

The implementation of CCS is not only affected by the firm's environmental capabilities, but also simultaneously has an impact on the firm's financial performance. In addition, we consider the endogeneity issues due to reverse causality. Inspired by Andreou and Kellard (2021), we lag the control variables to mitigate concerns related to reverse causality. The regression results are shown in Table 4. In Column 1, we explore the relationship between CCS and ROA. The estimated coefficient of CCS is 0.0626 and is significant at the level of 0.05, which indicates that firms' implementation of CCS will lead to superior financial performance. The estimated coefficient of *Founder* is 0.3472 and is significant at the level of 0.05, which indicates that a CEO who is the founder, pays more attention to the firm's financial performance to seek efficient development of the firm. The estimated coefficients of *Boardv* and *Empv* are -0.3692 and -0.3193 and are both significant at the level of 0.05. Leadership and employees' vision of environmental capabilities will damage the interests of some firms, which is the cost of firm environmental development. The estimated coefficient of *Strategy* is 0.3295 and is marginally significant at the level of 0.01. We can find that when firms integrate climate-related issues into their business strategies, they can achieve coordinated development of emission reduction strategies and financial performance. *Strategy* is a positive driving force of *ROA,* but *Oppo* may have no impact, which suggests prioritizing strategic integration over opportunity seeking. The estimated coefficient of *Ets* is -0.1503 and is marginally significant at the level of 0.1, which indicates that firms under ETS will be subject to pressure to reduce emissions and may lose some of their financial

Table 3. Regression results with log(CCS) as dependents

Independent variables/statistics	Dependent variables
	CCS
Management attention	
Independent	-0.1498*** (0.0470)
Founder	-1.1114*** (0.3360)
Shared vision.	
Boardv	6.0628*** (1.2177)
Empv	-1.9263* (1.0498)
Environmental strategy proactivity.	
Oppo	0.8771** (0.3897)
Strategy	-2.6609** (1.1943)
Continuous innovation.	
Ets	-0.1368 (0.4959)
Lowpro	0.0026 (0.0038)
Control variables.	
Int	0.6234** (0.2757)
Slack	1.5277** (0.7559)
Lev	-0.1909 (0.1706)
Mb	3.628*** (1.0993)
Carbon	2.6125*** (0.8344)
N	145
R^2	0.4673
F	55.6390

Note. *CCS* is the dependent variable in the regression. Standard errors are clustered at the firm level and shown in parentheses. *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$.

benefits to meet emission reduction requirements. Our study shows that all four dimensions of environmental capabilities are strongly associated with ROA. The implementation of CCS also has a positive impact on ROA. Slack resources, the increase in the market-to-book ratio, and the firms' positive emissions are all conducive to improving ROA. However, the increase in intelligence does not bring higher financial performance to firms.

In Column 2, we lagged the control variable for the first order to mitigate ROA's concerns about inverse causality in CCS. We find the estimated coefficient of *CCS* is 0.0548 and is significant at the level of 0.05, indicating that the treatment of endogenous is effective. In Column 3, we explore the mediating effect of *Int*. The estimated coefficient of *CCS* is 0.0916 and is significant at the level of 0.1, which indicate that CCS can achieve financial performance by increasing the AI technology. In Column 4, we explore the effect of *Int* and *CCS* on *ROA*. The estimated coefficient of *CCS* is 0.0647 and is significant at the level of 0.05. The estimated coefficient of *Int* is 0.023 and is significant at the level of 0.1. It indicates that *Int* acts as a partial mediator between *CCS* and *ROA*. Through the exploration of the relationship between *CCS* and *ROA*, the test mediating effect of *Intelligentize* are satisfied. Therefore, *CCS* can improve *ROA* by increasing the use of AI technology.

The Impact of Firm Characteristics on CCS and Environmental Capabilities

Further, we consider the impact of enterprise characteristics on CCS implementation and its economic consequences. We first consider the impact of firm size. We based on the median number of employees and divide sample into two subsamples. The regression results are shown in Table 5. The results show that CCS has a significantly positive correlation with *ROA*. However, when small and medium-sized firms (below the 50th percentile) have implemented CCS, the effects of CCS on increased financial performance are insignificant. This may be the reflection of the cost of implementing CCS. For small and medium-sized firms, their revenue may be insufficient from the implementation of costly CCS technology.

We then consider the impact of the degree of the firm's carbon dependency. We classify manufacturing, transportation services, power generation, infrastructure, fossil fuels, and mineral extraction as industries with high carbon dependency. Table 6 shows the regression results. The results show that *CCS* has a significantly positive correlation with *ROA* in highly carbon-dependent sectors. Firms in highly carbon-dependent sectors rely more heavily on fossil fuels and are less likely to reduce fuel use significantly. In contrast, CCS technology has become the preferred choice for firms in highly carbon-dependent sectors without reducing emissions.

DISCUSSION

As organizations globally accelerate their efforts to reduce emissions, aligning with the ambitious 2 °C target, it is becoming evident that strategies focused solely on reducing fossil fuel use and improving low-carbon technologies are inadequate in the broader context of climate change mitigation. CCS is increasingly recognized as a pivotal technology in this battle against climate change, critical for meeting the ambitious global warming targets established by the IPCC and echoed in the COP21 agreements (Durán-Romero et al., 2020). Despite the recognition of CCS and negative emissions technologies (NETs) for their advanced technical capabilities, the actual pace of CCS deployment remains slower than what is required to effectively meet global climate goals (Bui et al., 2018). In response, a growing number of countries are initiating large-scale CCS projects, demonstrating a commitment to fostering corporate engagement with this technology (Ko et al., 2021; Kang et al., 2021).

While prior research has largely centered on the feasibility and technological development of CCS, our study broadens the scope by examining CCS's actual role as a mechanism for emission reduction at the firm level and the benefits it entails. The study also delves into the potential of AI technology, represented by our mediating variable 'Int', to further enhance CCS technology. The emergence of quantum computing has promoted AI development by solving many complex problems that traditional computing methods cannot solve (Gill et al., 2024). Advancements in AI have opened new avenues for environmentally friendly innovations, notably improving energy efficiency. Quantum computing offers the potential to solve specific climate-relevant issues (Deloitte, 2023). As a state-of-the-art approach for CO_2 capture and storage, CCS stands to gain significantly in terms of efficiency and

Table 4. Regression results for assessing the financial performance implications of CCS and environmental capabilities

Independent variables/statistics	Dependent variables			
	ROA		*Int*	*ROA*
CCS	0.0626** (0.0269)	0.0548** (0.0220)	0.0916* (0.0472)	0.0647** (0.0274)
Int				0.0230*
				(0.0625)
Management attention.				
Independent	0.0113 (0.0089)	0.0124* (0.0065)	0.0060 (0.0175)	0.0115 (0.0090)
Founder	0.3472** (0.1466)	0.6332*** (0.2024)	-0.0935 (0.3234)	0.3451** (0.1514)
Shared vision.				
Boardv	-0.3692** (0.1716)	-0.3732** (0.1453)	-0.1506 (0.4537)	-0.3727** (0.1687)
Empv	-0.3193*** (0.0966)	-0.4674*** (0.0848)	0.5631 (0.3842)	-0.3064*** (0.0953)
Environmental strategy proactivity.				
Oppo	-0.0708 (0.0987)	-0.1556 (0.1024)	-0.1025 (0.2619)	-0.0732 (0.0986)
Strategy	0.3295*** (0.1013)	0.4908*** (0.1242)	0.5816 (0.4061)	0.3428*** (0.1116)
Continuous innovation.				
Ets	-0.1503* (0.082)	-0.1875*** (0.0702)	0.5106* (0.2931)	-0.1386* (0.0828)
Lowpro	0.0597 (0.0807)	0.0006 (0.0006)	-0.0016 (0.0020)	0.0006 (0.0008)
Control variables.				
Slack	-0.2922*** (0.0966)		-0.0703 (0.2926)	-0.2938*** (0.0979)
Lev	-0.0007 (0.0693)		0.0194 (0.1459)	-0.0002 (0.0699)
Mb	0.5428*** (0.1852)		-0.2173 (0.5324)	0.5378*** (0.1867)
Carbon	-0.1620 (0.2146)		-0.9430** (0.4218)	-0.1837 (0.1267)
L.Slack		0.1922*** (0.0636)		
L.Lev		-0.0048 (0.0491)		
L.Mb		-0.0320 (0.0613)		
L.Carbon		0.0076 (0.0074)		
N	145	155	145	145.

continued on following page

Table 4. Continued

Independent variables/statistics	Dependent variables			
	ROA		*Int*	*ROA*
R^2	0.5461	0.4263	0.2784	0.5475.
F	106.5971	10.9095	2.4639	854.9786

Note. *ROA* is the dependent variable in the regression. Standard errors are clustered at the firm level and shown in parentheses. **p* < 0.10; ***p* < 0.05; ****p* < 0.01.

Table 5. Subsample analysis: Firm size

	ROA	
	Below 50th percentile	**Above 50th percentile**
CCS	0.0019	0.0730***.
	(0.0226)	(0.0072).
Control variables	Yes	Yes
Firm fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	111	34.
R^2	0.9815	0.998.
F	24.7940	113.0.

Note. Standard errors are clustered at the firm level and shown in parentheses. *p < 0.10; **p < 0.05; ***p < 0.01.

cost-effectiveness by integrating intelligent technologies. This decrease in technological costs emerges as a powerful incentive for firms to embrace CCS, underlining its viability as a pragmatic and advantageous response to the challenges posed by climate change. This extended analysis underscores the transformative potential of CCS when combined with AI, highlighting its role not just as a technological solution but as a strategic asset in the corporate fight against climate change.

Compared to ongoing oil extraction ventures, renewable energy projects face substantially higher initial costs. This factor, compounded by the current global inflationary trend, elevates the expense of

Table 6. Subsample analysis: Carbon dependency

	ROA	
	Low carbon dependency sectors	**High carbon dependency sectors**
CCS	0.1488	0.0742**
	(0.1092)	(0.0351)
Control variables	Yes	Yes
Firm fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	62	83
R^2	0.9926	0.9697
F	32.9111	13.2629

Note. Standard errors are clustered at the firm level and shown in parentheses. *p < 0.10; **p < 0.05; ***p < 0.01.

financing renewable projects through debt, thus decelerating their adoption. Deka and Dube (2021) indicated a positive correlation between inflation rates and renewable energy costs, suggesting that the shift away from fossil fuels is experiencing a temporary slowdown. The adoption of CCS serves as a strategic response to this deceleration, mitigating the transition's negative impacts. Nonetheless, it's anticipated that the future utilization of renewable energy will foster a low-carbon environment and stimulate economic growth.

Like any technology aimed at reducing carbon emissions, the development of CCS involves significant costs, especially for initial projects. These initial projects are crucial as they lay the foundation for the necessary transport and storage (T&S) infrastructure, which will benefit subsequent ventures. Consequently, for many firms, particularly small and medium-sized enterprises or those with low carbon intensity, the steep upfront costs pose a substantial barrier to adopting this technology, a finding supported by our empirical results.

Bui et al. (2018) argued that a robust CCS industry could contribute significantly to the economy's gross value. Many current CCS programs include financial incentives to help offset the costs, thereby encouraging private sector investment in developing, deploying, and utilizing CCS technology. However, achieving a fully integrated CCS infrastructure and projects solely through private investment remains challenging. Public sector involvement and supportive governmental policies are vital. Governments need to deliberate the role of CCS in their long-term low-carbon energy strategies and actively promote the feasibility of CCS as a cost-effective method for decarbonizing power generation and other energy-intensive industries. Setting specific environmental technology milestones, with interim progress assessments and penalties for non-compliance, is crucial. Addressing climate challenges effectively will require "technology forcing" strategies, including executive actions (Phillips, 2022).

Our findings have significant implications for business decision-making. Firstly, the biggest concern for firms adopting CCS is the stagnation of financial performance due to high costs. Our study found that CCS can improve corporate financial performance, and CCS technology was necessary but not widely used. That is because, while organizations that adopt CCS can offset their high costs in the long run, this expense remains a challenge for most firms in the short term. Using CCS technology necessitates exploring diverse funding strategies that effectively distribute the financial burden among major carbon emitters. Given its unique ability to address carbon reduction across various sectors, CCS is a pivotal technology for comprehensive environmental strategies. For businesses, particularly those in high-emission industries, adopting CCS not only aligns with environmental goals but also presents a long-term, sustainable investment. Companies must reassess and realign their operational strategies across the four key dimensions of environmental capabilities to effectively integrate CCS into their business models. For investors, firms that adopt CCS do not deliver short-term financial returns, but they are worth investing in in the long run. For the government, our research offers guidance on how governments can effectively support firms to reduce emissions.

This research, while providing valuable insights, is limited by its focus on listed firms. These firms, typically under greater regulatory scrutiny, are more inclined to adopt low-carbon technologies and environmental strategies, often driven by the need to maintain a positive public image. This inclination might not be as pronounced in unlisted firms, which often operate under less scrutiny and may prioritize profitability over environmental considerations. To gain a more comprehensive understanding of CCS adoption across different business landscapes, future research should encompass a broader range of companies, including those not publicly listed. Moreover, the study's reliance on U.S.-based data points to a geographical limitation. The dynamics of environmental strategy adoption and the effectiveness of technologies like CCS can vary greatly across different regions, influenced by factors such as local climate conditions, economic structures, governmental policies, and the level of technological advancement. Therefore, expanding the scope of research to include data from other countries would provide a more global perspective on the adoption and impact of CCS technologies. Another limitation of the current study is the reliance on data from the 2017–2019 period from the

CDP reports. While this timeframe provides a snapshot, it does not capture the full evolution and long-term trends in CCS adoption. Future studies should aim to include a more extensive set of data spanning a longer period. This would allow for a more robust analysis that could track changes over time and provide deeper insights into the trends and patterns in CCS adoption. Lastly, the potential for a rebound effect, where companies might increase fossil fuel usage due to the availability of CCS as a mitigation strategy, warrants further investigation. This phenomenon could counteract the environmental benefits of CCS and needs to be carefully studied to ensure that CCS technologies contribute effectively to overall emission reduction goals. Future research should explore this aspect to understand better the full implications of CCS technology in the broader context of global carbon emissions reduction efforts.

CONCLUSION

This paper explores the factors at the firm level that affect the deployment of CCS and their economic ramifications, employing an econometric model to dissect these elements and scrutinizing the role of AI in this arena. By analyzing secondary data from U.S.-listed companies reported by CDP, this study investigates the motivations behind firms' adoption of CCS. It assesses the financial implications of integrating CCS and AI technologies. Our findings reveal that a firm's environmental capabilities, particularly when augmented with AI, significantly influence the adoption and effective implementation of CCS, resulting in notable improvements in financial performance. This relationship is further nuanced by considerations such as the size of the firm and the extent of its reliance on carbon-intensive processes.

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