

Article

CCUS Development in China: Influencing Factors via Structural Equation Modeling

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Abstract

We address the growing urgency of climate action and China's pivotal role in advancing carbon capture, utilization, and storage (CCUS) toward its "dual carbon" goals. This study examines factors influencing CCUS development in China using structural equation modeling (SEM), identifying five critical determinants: resources, environment, market, technology, and government–society dimensions. Empirical data from expert surveys underscore the need for integrated policy measures, including fiscal incentives, standardized evaluation, international cooperation, and energy infrastructure upgrades. The findings enable effective decarbonization and provide a transferable framework for emerging economies.

Keywords: CCUS; carbon dioxide; structural equation modeling; carbon neutralization; carbon emissions

1. Introduction

The global community faces escalating climate challenges driven by rising greenhouse gas emissions. Global carbon dioxide emissions have reached approximately 30 billion tons annually since 2006, with large and medium-sized stationary sources contributing about 60% of these emissions [1]. The overabundance of CO₂-dominated greenhouse gases significantly contributes to planetary heating, triggering multiple environmental disturbances [2]. According to the United Nations Framework Convention on Climate Change (UNFCCC), the escalating frequency and intensity of meteorological catastrophes empirically validate the accelerating deterioration of Earth's climatic equilibrium [3]. Research by both the IPCC and International Energy Agency (IEA) indicates that CCUS technologies will be instrumental in achieving 2050 carbon neutrality targets, potentially delivering one-sixth of the CO₂ reductions required to maintain the temperature rise capped at 1.5 °C under the Paris Agreement [4,5]. Carbon dioxide is widely recognized as the primary greenhouse gas requiring mitigation [6], prompting nations worldwide to establish emissions reduction policies and international climate agreements.

Against this backdrop, CCUS is a critical technology for addressing global climate change, enabling not only CO₂ sequestration but also its recycling for practical applications. The integrated process involves capturing CO₂ from major emission sources such as power and industrial plants, transporting it via pipelines or other means, and storing or



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utilizing it effectively [7,8]. This approach provides dual advantages—transforming CO₂ into valuable products while delivering economic benefits, and playing a vital role in reducing greenhouse gas emissions and removing atmospheric carbon [9,10]. Key stages include carbon capture through methods like chemical absorption, transport primarily via pipelines, and storage in geological formations or through mineralization. Each phase requires advanced technical systems to ensure efficiency and reliability.

Major nations, including the United States, Canada, European countries, and Australia, are actively advancing carbon capture, utilization, and storage (CCUS) research. In 2000, the U.S.–Canada Weyburn project enhanced oil recovery while capturing more than 26 million tons of CO₂ from synthetic fuels and power plants [11]. Canada's Quest program, since 2015, has injected CO₂ from oil-to-hydrogen processes into brine formations, storing 4 million tons by 2019 at reduced cost [12]. European examples include Norway's Sleipner and Snøhvit projects, Croatia's CO₂-EOR, and Iceland's Hellisheidi geothermal facility [13,14].

Bioenergy with carbon capture and sequestration (BECCS) and direct air capture and carbon storage (DACCS) are emerging as key negative-emission technologies. BECCS could reduce CO₂ emissions by 1 billion tons by 2050, while DACCS is expected to grow in importance post-2050 [15]. The Gorgon LNG project in Australia captures and injects 3–4 million metric tons of CO₂ annually into a saline formation [16]. As of 2023, the Americas host 29 operational CCUS facilities—24 in the U.S., 4 in Canada, and 1 in Brazil—accounting for 67% of global capacity and capturing 30 million metric tons per year, largely in fossil-fuel sectors [17]. The U.S. leads in technology development, bolstered by regulatory and fiscal support for CCUS-EOR, aligning economic and environmental goals [18].

China has solidified its role in global climate governance through its commitments to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [19]. As the world's largest carbon emitter since 2006, responsible for 25% of global emissions [20], China faces significant decarbonization challenges due to coal's dominance in its energy mix.

Carbon capture, utilization, and storage (CCUS) technology is critical for China's climate strategy, with theoretical sequestration potential estimated at 1.21–4.13 trillion tons. Projections indicate CCUS could mitigate 600 million to 2.1 billion tons of CO₂ annually by 2060 [21]. Since initiating CCUS development through the 2006 Xiangshan Conference, China has established over 120 demonstration projects by 2025, primarily in the petroleum, coal chemical, and power sectors, with an annual capture capacity reaching 6 million tons [22]. However, many large-scale projects initiated between 2014 and 2020 were delayed or suspended [23].

Institutional frameworks show progress, with the national carbon market launched in 2021, integrating 4 Gt CO₂ emissions annually [24]. Nevertheless, systemic barriers persist: integrated large-scale projects remain scarce, key technologies lag international standards, and policy incentives prove insufficient [25]. Current CCUS operations mitigate less than 0.0003% of national emissions, highlighting the urgent need for accelerated development.

This study investigates constraints hindering CCUS advancement through expert surveys targeting academic and research institutions. Findings aim to inform policy optimization and technological roadmaps critical for achieving China's 2030/2060 climate objectives while balancing energy security and economic competitiveness.

This paper will process the questionnaire survey data using structural equation modeling. This method explores key factors hindering CCUS development. Furthermore, this analysis will provide guidance for government entities and business organizations to promote the development of CCUS in China in order to reduce greenhouse gas emissions.

The innovations in this paper are as follows:

Analyze influencing factors using a holistic, multi-dimensional framework.

At present, most of the articles on CCUS focus on a single factor that influences the development of one of the CCUS processes, such as the technology of the capture process. In contrast, this paper focuses on the comprehensive consideration of these influencing factors from the aspects of resource, environment, market, technology, government and society, etc., and researches the interactions between these factors and their impacts on the development of CCUS. This research contributes to addressing important knowledge gaps in the CCUS development literature. In terms of technology, domestic and international research on CCUS is based on quantitative analysis. At present, most of the international CCUS environmental risk assessment, guided by the relevant guidelines and regulations, choose the evaluation method that is mainly qualitative, and most of the domestic and international studies still choose the analytical method that is mainly qualitative in terms of the payment of resources and society and government. This paper qualitatively analyzes the multiple factors affecting the development of CCUS through the questionnaire method. Structural equation modeling techniques are applied to conduct qualitative analysis of relevant factors. By combining qualitative and quantitative approaches, this research delivers findings broader in scope and analytical depth.

The remainder of this paper is structured as follows: Section 2 reviews the literature and establishes the theoretical hypotheses. Section 3 defines the research model and hypotheses. Section 4 describes the data collection and methodology. Section 5 performs the empirical analysis and interprets the results. Section 6 discusses policy implications and compares with existing literature. Section 7 presents the final conclusions. Section 8 outlines the study's limitations.

2. Literature Review

Peer-reviewed studies confirm five critical factors that shape the development of CCUS projects in China: technology, resources, environment, market, and government and society. These factors are supported by mature research results in the field of CCUS, covering the core links of CCUS development, and laying a solid foundation for the subsequent literature review.

2.1. Technology (Core Foundation for CCUS Development)

As the core foundation of CCUS development, technological advancement directly determines the feasibility and safety of CCUS projects, which is also the primary premise for the smooth implementation of subsequent research. CCUS is a vital technological solution for mitigating carbon dioxide emissions and supporting climate goals, as recognized by the IPCC AR6 report, which highlights its role in avoiding substantial cost increases in decarbonization pathways [26]. Achieving large-scale industrialization of CCUS would significantly reduce the costs of emission control across key sectors such as energy and chemical production, thereby providing crucial technical support for China's 2030 and 2060 climate targets [27]. Current research focuses on advancing all technological aspects, where technological readiness is a fundamental determinant for successful implementation [28]. However, current applications in China remain relatively limited, indicating a need for improved technological maturity [29]. Innovations in capture technology, such as the [DETA]Lys/NMP biphasic system, demonstrate exceptional performance with high CO₂ capacity and significantly reduced regeneration energy, highlighting strong potential for industrial application [30]. Advancements in transportation and storage are equally critical. Upgrading conveying equipment and developing high-efficiency compressors and corrosion-resistant materials can effectively reduce CO₂ transport costs and risks [31,32]. Furthermore, optimized storage systems enhance efficiency and safety, with CCUS-EOR

technologies effectively managing risks while creating economic value through enhanced oil recovery and permanent CO₂ storage [33,34]. Continued investment in core CCUS technologies remains essential to enhance performance reliability and meet implementation requirements across industrial and energy sectors [35]. The existing literature in this domain mostly focuses on technological readiness levels (TRLs) and energy consumption indicators, employing engineering–economic modeling and industrial pilot data, and generally concludes that technical maturity and cost reduction are the primary determinants of project feasibility.

2.2. *Environment (Ecological Constraints for CCUS Development)*

Environmental factors are the key constraints for the green development of CCUS, involving environmental protection requirements, ecological risks, and the coordination between project construction and ecological protection. In addition to regulatory frameworks, technical advancement, and policy mechanisms, environmental protection considerations significantly influence CCUS technology development pathways. Research in the environmental field has focused on the impact of CCUS technology on ecosystems and natural resources. The scaling up of CO₂ transport technology is conducive to reducing the overall cost and improving the efficiency of CCUS, establishing crucial foundations for commercial-scale CCUS implementation. Studies have shown that geologically sequestered CO₂ has a low risk of leakage and can be safely sequestered for thousands of years [36]. In addition, CCUS technology can reduce dependence on fossil fuels, thereby reducing air pollution and greenhouse gas emissions [37]. However, CCUS technology also faces a number of environmental challenges, and geologic sequestration requires careful siting and monitoring to ensure that carbon dioxide does not leak into the environment. Advanced carbon capture innovations will fundamentally reshape CCUS deployment trajectories within China's industrial framework [38]. Previous studies typically utilize leakage risk and environmental impact indicators as core variables, using life cycle assessment (LCA) and environmental monitoring data, consistently emphasizing that stringent monitoring and safety standards are critical constraints for large-scale deployment.

2.3. *Resources (Material Basis for CCUS Implementation)*

Resource endowment is the material basis for CCUS development, which includes the supply of raw materials, the layout of storage sites, and the guarantee of infrastructure, all of which are indispensable for the stable operation of CCUS projects. CCUS technology is highly relevant to the resource sector, with CO₂-enhanced oil recovery (EOR) being a primary application [39]. Injecting CO₂ into oil fields can boost crude production, extending field life and reducing the need for new developments [40]. Furthermore, captured CO₂ can be utilized in synthesizing fuels and manufacturing building materials, thereby decreasing reliance on fossil fuels and conventional resources [41]. However, CCUS implementation faces challenges, including high capture and sequestration costs, necessitating more cost-effective technologies. Using CO₂ for EOR also requires careful monitoring due to potential impacts on reservoir integrity [42].

The phase and purity of CO₂ significantly influence technical requirements and costs. Capturing gaseous CO₂, the predominant form in Chinese industrial emissions, is costly. In contrast, liquid or solid CO₂ facilitates transport and storage but requires additional conversion equipment, affecting economic feasibility. High-purity CO₂ streams improve EOR and geological storage efficiency and safety. However, industrial CO₂ in China often contains impurities like nitrogen and oxygen, increasing capture and purification complexity and cost. A stable, high-purity CO₂ supply is crucial for the feasibility and economy of CCUS projects. China's substantial industrial emissions provide abundant CO₂

sources for CCUS applications [20]. Research in this area frequently integrates storage capacity and CO₂ utilization rates as key variables, applying geological assessment methods and regional survey data, and generally finds that resource endowment and infrastructure proximity are foundational to project scale and location.

2.4. Market Mechanism (Driving Force for CCUS Industrialization)

The market mechanism provides the driving force for the sustainable development of CCUS, including the allocation of market resources, the formulation of price mechanisms, and the guidance of market demand. Studies indicate that carbon quota trading frameworks between emission sources can facilitate effective CO₂ sequestration and utilization while simultaneously reducing the economic burden associated with low-carbon production, demonstrating quota trading's significant role in promoting CCUS technology adoption [6,43]. Furthermore, carbon market development not only enables CCUS to achieve meaningful emissions reductions but also leverages market mechanisms to optimize quota resource allocation and expand trading channels, thereby reducing transaction costs [44]. The introduction of well-designed market mechanisms can help achieve balanced economic and environmental development [45].

Case studies from southern Iraqi oilfields demonstrate that CCUS economic benefits are influenced by oil and carbon market prices, with differently sized operations adopting varying strategies based on price conditions [46]. This provides valuable insights for CCUS implementation in China: the Chinese carbon market remains in its nascent and developmental phases compared to established markets in the European Union, the United States, and other advanced economies. China must therefore expedite carbon market development, focusing particularly on establishing total trading volumes, exchange mechanisms, and the development and implementation of price stabilization instruments. Additionally, strengthening legal frameworks for carbon markets and clarifying non-performing asset handling are essential [47]. Existing literature mostly centers on carbon price volatility and investment return variables, using cost-benefit analysis and market simulation based on transaction data, and commonly concludes that robust carbon trading incentives are vital for sustainable industrialization.

2.5. Government and Society (Institutional Guarantee for CCUS Development)

Government policies and social acceptance are important institutional guarantees for CCUS development, which provide policy support and public support for the orderly development of CCUS projects. Government policies are crucial in supporting and guiding CCUS technology development [22]. Through frameworks and incentives such as subsidies, tax benefits, and research and development (R&D) funding, governments provide strategic direction and attract investment from enterprises and research institutions [48]. These measures have effectively promoted CCUS application in China's energy-intensive sectors. However, potential environmental and community risks exist, including CO₂ leakage that could contaminate groundwater and soil, as well as impacts on local ecosystems and resident wellbeing [22,48]. Therefore, ensuring the long-term viability of CCUS requires policies that incorporate strict safety standards, enhanced oversight, and public participation to ensure social acceptance and project sustainability [49]. Strategic CCUS advancement thus necessitates integrating policy mechanisms with technical infrastructures to establish sustainable operational enablers within China's decarbonization landscape [50]. Previous studies often combine policy intensity and public perception variables, utilizing qualitative analysis or survey-based methods, and universally conclude that institutional support and social acceptance are the decisive guarantees for long-term project viability.

In summary, sustainably advancing CCUS requires coordinated integration of policy frameworks, technological innovations, and industrial ecosystems, ensuring systemic enablers for China's low-carbon transition strategies. Studying these related factors will help provide policy recommendations and technical support for the development of CCUS in China and promote the widespread application and popularization of this technology in China.

3. Research Model and Hypotheses

To ensure clarity and avoid ambiguity, we define each core construct and its measurement dimensions as follows:

Resources (R): In this study, "resources" refer to the natural and material conditions required for the development of CCUS projects in China, including CO₂ concentration, purity, phase state, geological storage potential, and supporting infrastructure. The construct is measured by five items in the questionnaire, covering raw material availability, geological sequestration conditions, and supply system completeness.

Environment (EN): "Environment" in this context denotes the technical and ecological constraints of CCUS development, including CO₂ transportation technology maturity, environmental pollution risks of solvents, and CO₂ sequestration safety. These dimensions are operationalized through three survey items focusing on technical maturity and pollution concerns.

Market (M): "Market" refers to the economic drivers shaping CCUS development in China, including fossil fuel prices, carbon pricing mechanisms, and the maturity of the carbon market. The construct is measured by three items reflecting economic incentives and market development conditions.

Technology (T): "Technology" refers to the technical maturity and operational safety of core CCUS processes, including CO₂ absorption, transportation, injection/extraction, and enhanced oil recovery (EOR). The construct is operationalized by five items covering energy consumption, equipment level, and safety production technology.

Government and Society (GS): "Government and society" represents the institutional and social support for CCUS development, including investor willingness, regulatory frameworks (e.g., subsidy policies), and public support for technological research and development. The construct is measured by three items focusing on policy, investment, and social acceptance.

CCUS Development (D): The dependent variable "CCUS development" is defined as the overall progress and improvement of CCUS programs in China, including the system's performance over time and its contribution to national carbon emission reduction goals.

The analytical framework (Figure 1) defines five pivotal drivers shaping China's CCUS development trajectories: resources-oriented, environmental, market, technological, and governmental and societal. We hypothesize that the five factors of resources, market, environment, technology, and government and society have a direct positive influence on the development of CCUS. At the same time, we hypothesize that there is a potential mutual influence relationship between each influencing factor, as shown in Figure 1.

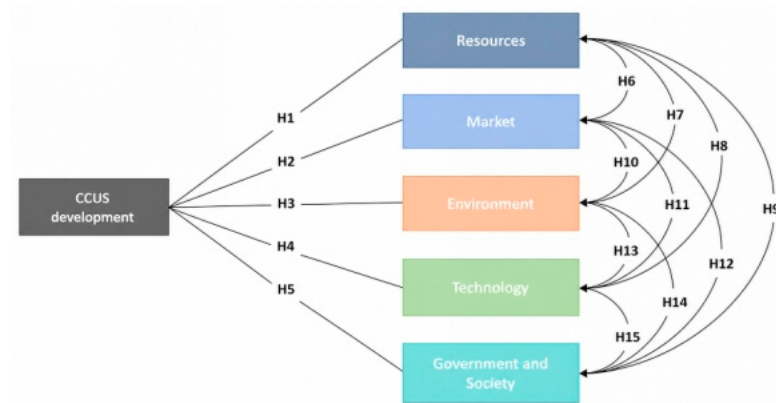


Figure 1. Research model.

4. Materials and Methods

4.1. Questionnaires

As a primary data collection tool in empirical research, questionnaire surveys employ standardized items to systematically examine targeted research questions. These instruments typically exist in two distinct formats based on their delivery mechanisms: conventional paper questionnaires and modern electronic versions. The adoption of electronic survey methods is increasingly supported in the literature for its ability to predict behavioral intentions and reach specialized professional cohorts effectively [51]. The Quick Response (QR) code-based survey method, as a technological innovation in data gathering, overcomes key constraints inherent to traditional passive approaches—namely, reliance on specific devices, time limitations, and environmental barriers. This aligns with the methodological evolution observed in technology acceptance studies, where digital tools facilitate the collection of data from diverse and geographically dispersed respondents [52]. Unlike conventional methods demanding in-person participation and manual responses, this approach allows respondents to actively complete surveys using mobile devices via QR code scanning. This evolution not only improves spatiotemporal adaptability in survey implementation but also lowers administrative hurdles and cost expenditures. Participants can access and submit questionnaires through mobile networks during intermittent periods, enhancing participation rates and response accuracy. From a methodological perspective, this transition from physical to digital formats illustrates how social science research methodologies have evolved in response to mobile internet technologies. By incorporating a resume-from-breakpoint function (allowing respondents to continue unfinished questionnaires upon subsequent logins), the design effectively capitalizes on participants' fragmented time segments. The QR code-embedded questionnaire has been systematically distributed to three targeted groups: university faculty in relevant disciplines, professionals from related industries, and researchers at scientific institutions, enabling them to complete and disseminate the survey through autonomous participation channels.

Survey instruments can be categorized into paper-based and digital formats according to their distinct data collection methods. However, the emerging QR code methodology fundamentally transforms traditional passive survey mechanisms by overcoming systemic spatiotemporal constraints. Compared with conventional approaches, this innovative technique enables participants to autonomously complete questionnaires through mobile smart terminal scanning, thereby significantly reducing implementation barriers and operational costs. The research ultimately distributed 1058 survey forms, with 218 valid responses successfully recovered, yielding an effective response rate of 20.6%.

4.2. Questionnaire Design and Data Collection

In order to ensure the collected data accurately represent real-world conditions, we used various methods in designing the questionnaire. The design process followed the rigorous psychometric procedures established in seminal operations management and social system research, ensuring that each measurement item corresponds to a validated theoretical construct [53]. The study framework was constructed through rigorous organization and critical appraisal of extant literature. Progressive iterations involving experts' feedback were then implemented, ultimately yielding an enhanced questionnaire through evidence-based refinements derived from collaborative deliberations. The survey instrument comprised 26 items, with four explicitly dedicated to capturing respondents' demographic characteristics. This design balanced comprehensive data collection with ethical considerations by minimizing intrusive personal inquiries. The CCUS determinants assessment adopted a 7-point Likert-type scale measurement system. Reliability and validity improve as the number of response categories increases from two to seven, but show only negligible gains beyond seven categories [54]. Furthermore, the use of a multi-point Likert scale is justified in complex socio-technical research to capture the magnitude and significance of explanatory variables with greater precision [55]. Therefore, a seven-point Likert scale was adopted to balance psychometric performance and respondent burden. This format also provides a neutral midpoint to avoid forced-choice responding. Employing a reverse-anchored scoring protocol, responses ranged from 1 (indicating strongest dissent) to 7 (representing complete concurrence), with ordinal progression reflecting ascending agreement intensity. (Refer to the questionnaire in Appendix A.) The study employed an electronically distributed structured survey targeting nationally recognized CCUS experts at leading academic institutions. Specifically, the QR code for the questionnaire was distributed through two primary channels. Academic channels included sending the QR code to faculty members and researchers in CCUS-related disciplines (including carbon capture technology, geological storage, and carbon policy) via university research groups, academic societies, and specialized email lists. Industry channels covered sharing the QR code with technical professionals in CCUS-related industries (such as carbon capture equipment manufacturing, oil and gas EOR, and carbon storage projects) through industry associations, enterprise technical teams, and professional working groups. This targeted selection of respondents based on professional expertise ensures the validity of the data for evaluating specialized technological intentions, as demonstrated in prior empirical studies on internet services and energy technologies [51,53]. Respondents were systematically selected on the basis of their academic research and expertise in specific areas of CCUS systems. All participants included in the survey are actively engaged in research or professional work directly related to CCUS, including carbon capture technologies, geological storage, carbon policy, and carbon market mechanisms. A total of 1058 questionnaires were distributed during the study, with 218 valid responses successfully collected. This resulted in a final effective recovery rate of 20.60%, reflecting the practical challenges inherent in large-scale survey administration. From the results of data analysis, the questionnaire adheres to the principles of systematic, convenient, scientific and rigorous questionnaire design.

4.3. Structural Equation Modeling (SEM)

This study contains 6 latent variables with a total of 20 observed items. The sample size of 218 exceeds the conventional threshold of 10 times the number of observed variables, fully satisfying the sample requirement for covariance-based SEM. Meanwhile, this study aims to verify theoretical hypotheses, so the traditional CB-SEM is adopted rather than PLS-SEM for methodological appropriateness. In quantitative research, structural equation modeling (SEM) is widely used to analyze complex variable relationships. The

method is defined as a combination of factor analysis and path analysis, enabling the evaluation of both measurement and structural models simultaneously [53,56]. The method works by studying patterns in covariance matrices—essentially, figuring out how different factors influence each other statistically. Unlike simpler models, SEM can handle multiple variables at once while testing theoretical frameworks. Given the inherent challenges in operationalizing CCUS developmental determinants (theoretical constructs under study), these multidimensional phenomena require measurement through empirically observable proxy indicators, formally categorized as latent variables within structural equation modeling frameworks. Following the standard specification phases of SEM [56], the model was structured to map the interactions between manifest variables and their underlying concepts. While structural equations include measurable variables (like survey responses) and hidden factors (like attitudes), their real strength lies in mapping two types of relationships: how measured data connect to underlying concepts, and how those concepts themselves interact. This makes SEM more versatile than basic statistical models. The measurement model in this dissertation serves the following functions:

$$x = \Lambda_x \xi + \delta \quad (1)$$

where x denotes exogenous observed variables; Λ_x denotes the x factor loading matrix; ξ is the exogenous latent variable; and δ is the residual vector of the equation.

The functions of the structural model in this study are as follows:

$$y = \Lambda_y \eta + \varepsilon \quad (2)$$

where y denotes endogenous observed variables; Λ_y denotes the y factor loading matrix; η is the endogenous latent variable; and ε is the residual vector of the equation.

The measurement model in this dissertation serves the following functions:

$$\eta = B\eta + \Gamma\xi + \zeta \quad (3)$$

In this structural equation model, η stands for the endogenous latent variable—the one that gets influenced by other factors—while ξ represents the exogenous latent variable, acting as the independent driver in the system. The matrix B shows how strongly the endogenous variables affect each other, and Γ measures the impact of those external factors on the endogenous ones. Finally, ζ , as the residual term, captures the variation that the model has not yet explained.

4.4. Sample Characterization Distribution Description

The data in Table 1 describe the distribution of sample characteristics and show the distribution of the sample characteristics counted after this survey, including gender, age, education level, occupation.

From the data describing the distribution of the characteristics of the sample in the table, 54.13% of the statistical sample are men and 45.87% are women, which is a balanced distribution of men and women in the sample.

Educational attainment analysis indicated universal postgraduate standing within the sample population. Stratification emerged with Master's holders representing 55.96% and PhD recipients accounting for 44.04% of the participant pool. This shows that the sample data are all professionals with higher education.

Table 1. Description of the distribution of sample characteristics.

Variant	Options	Frequency	Percentage
Gender	male	118	54.13%
	female	100	45.87%
Age	19–30 years	52	23.85%
	31–45 years	108	49.54%
	46–60 years	46	21.10%
	60 years and over	12	5.51%
	College or bachelor's degree	0	0%
Educational Attainment	Master's degree holders	122	55.96%
	PhD holders	96	44.04%
	Other	0	0%
	College/University students	20	9.17%
Careers	Scientific researcher	32	14.68%
	Higher-education teachers	135	61.93%
	Other	31	14.22%

In terms of age, the questionnaire mainly surveyed people over 19 years old, and the sample was divided into four gradients. Most participants in the study—over 70%—were between 31 and 60 years old. Breaking it down further, 49.54% were in the 31–45 age group, and about 21.10% fell into the 46–60 range. This shows that middle-aged individuals made up the majority of the sample. The rest of the population was 23.85% aged 19–30 and 5.51% aged 60 and above. The age distribution skews significantly toward middle-aged and elderly demographics.

College teachers made up the largest group at 61.93%, while researchers accounted for 14.68% and graduate/doctoral students for 9.17%. The rest—about 14.22%—came from other professions, showing that the study mainly attracted people working in or connected to academia. It can be seen that the sample is mainly concentrated among senior intellectuals, accounting for 76.61%.

Overall, the sample satisfies the requirement of recruiting senior intellectuals with professional research experience in the field. All respondents specialize in CCUS-related disciplines, including energy engineering, environmental science, and carbon management, demonstrating strong pertinence and professional competence of the sample.

5. Calculations

5.1. Descriptive Statistics and Normality Analysis

Before conducting reliability and validity analysis, descriptive statistics and normality checks were performed to assess the distributional qualities of the measurement items included in the structural equation model. As shown in Table 2, the mean values of the items range from 4.477 to 5.197, with standard deviations between 1.448 and 1.720, indicating a reasonable degree of response variability. To examine the normality of the data, skewness and kurtosis values were calculated for each item. All skewness values fall between -0.720 and 0.066 , and all kurtosis values range from -0.912 to -0.256 . According to established guidelines for covariance-based SEM, skewness values within ± 2 and kurtosis values within ± 7 are considered acceptable for approximate normality [57]. Therefore, the data meet the required distributional assumptions for subsequent structural equation modeling.

Table 2. Normality test results for measurement items across dimensions of the influence factor scale.

Subject	Mean	Standard Deviation	Skewness	Kurtosis
R1	4.610	1.720	−0.257	−0.778
R3	4.697	1.649	−0.340	−0.654
R4	5.083	1.613	−0.720	−0.260
EN1	5.161	1.562	−0.592	−0.523
EN2	4.954	1.577	−0.536	−0.490
EN3	5.128	1.635	−0.668	−0.461
M1	4.477	1.546	−0.078	−0.779
M2	4.569	1.535	0.066	−0.912
M3	5.197	1.510	−0.591	−0.436
T1	5.018	1.554	−0.477	−0.683
T2	5.046	1.532	−0.504	−0.455
T3	5.041	1.653	−0.573	−0.568
T4	5.083	1.581	−0.638	−0.319
T5	4.995	1.636	−0.559	−0.531
GS1	5.110	1.591	−0.639	−0.479
GS2	5.050	1.537	−0.493	−0.579
GS3	5.023	1.570	−0.449	−0.662
D1	5.050	1.509	−0.549	−0.256
D2	4.807	1.530	−0.419	−0.501
D3	4.968	1.448	−0.385	−0.414

5.2. Multicollinearity Test

Before estimating the structural model, multicollinearity among the latent variables was assessed using variance inflation factors (VIFs). As shown in Table 3, all VIF values range from 1.299 to 2.442, which are well below the commonly accepted threshold of 5. This indicates that there is no severe multicollinearity among the variables in the model, and the parameter estimates are not affected by high collinearity.

Table 3. Multicollinearity test.

Independent Variables	Tolerance	VIF
R-mean	0.77	1.299
EN-mean	0.441	2.265
M-mean	0.621	1.61
T-mean	0.41	2.442
GS-mean	0.456	2.192

5.3. Reliability Analysis

Cronbach's coefficient was used to assess the reliability of the measurement tool. The coefficient ranges from 0 to 1, with higher values indicating better reliability [58]. The SPSS 27 calculation result shows that the Cronbach's α reliability coefficient is 0.941, indicating high internal consistency of the measurement scale (Table 4).

Table 4. Cronbach's α credibility coefficient assessment table.

Cronbach's Alpha Reliability Coefficient Assessment Scale	
>0.8	Very high
0.7–0.8	Good
0.6–0.7	Acceptable
<0.6	poor

5.4. Validity Analysis

Construct validity was tested using the Kaiser–Meyer–Olkin (KMO) index and Bartlett’s sphericity test. Values closer to 1 in KMO indicate stronger inter-variable correlations, while values near 0 indicate weak correlations. Bartlett’s test examines whether the correlation matrix differs significantly from an identity matrix; a significance of $p < 0.05$ confirms the applicability of factor analysis. According to methodological standards, $KMO > 0.5$ and Bartlett’s $p < 0.05$ are required for structural validity [59]. The SPSS analysis yielded a KMO of 0.928 and Bartlett’s test result of $p < 0.001$, meeting these thresholds (Table 5).

Table 5. Sample measurement assessment form.

KMO Sample Measurement Factor Analysis Stressors	
>0.9	Very adaptable
0.8–0.9	Fairly adaptable
0.7–0.8	Adaptation
0.6–0.7	More adaptable
0.5–0.6	Barely fit
<0.5	Not adapted

Convergent validity was evaluated using average variance extracted (AVE) and construct reliability (CR), calculated as follows:

$$AVE : \frac{\sum \lambda_k^2}{\sum \lambda_k^2 + \sum \text{var}(\varepsilon_k)} \quad (4)$$

$$CR : \frac{(\sum \lambda_k)^2}{(\sum \lambda_k)^2 + \sum \text{var}(\varepsilon_k)} \quad (5)$$

where λ_k denotes standardized factor loadings, and ε_k denotes measurement error variance. Factor loadings reflect the correlation between observed variables and latent constructs, and a threshold of 0.5 is generally adopted to judge good explanatory performance. The relevant results of convergent validity and composite reliability are shown in Table 6. All item factor loadings are higher than 0.5, and each latent dimension satisfies the standard of $AVE > 0.5$ and $CR > 0.7$, which verifies good convergent validity of the scale [60]. After removing items R2 and R5, the AVE of dimension R meets the convergent validity standard.

Table 6. Convergent validity and combined reliability tests for each scale of the impact factor scale.

Pathway Relationship			Estimate	AVE	CR
R1	<---	R	0.741	0.589	0.810
R3	<---	R	0.851		
R4	<---	R	0.702		
EN1	<---	EN	0.853	0.704	0.877
EN2	<---	EN	0.853		
EN3	<---	EN	0.81		
M1	<---	M	0.638	0.520	0.762
M2	<---	M	0.653		
M3	<---	M	0.853		
GS1	<---	GS	0.817	0.720	0.885
GS2	<---	GS	0.886		

Table 6. Cont.

Pathway Relationship			Estimate	AVE	CR
GS3	<---	GS	0.841	0.731	0.931
T1	<---	T	0.841		
T2	<---	T	0.851		
T3	<---	T	0.877		
T4	<---	T	0.85		
T5	<---	T	0.854	0.653	0.849
D1	<---	D	0.812		
D2	<---	D	0.839		
D3	<---	D	0.771		

5.5. Development of Structural Equation Model

Structural equation models for R1, R3, R4, EN1, EN2, EN3, M1, M2, M3, T1, T2, T3, T4, T5, GS1, GS2, GS3, D1, D2, and D3 were constructed using AMOS 28 software. Model refinements implemented through modification index diagnostics. Judge whether another iteration is needed based on the CFA indicator values output by the software. The computational outcomes are ultimately illustrated in Figure 2, although with a modified structural representation.

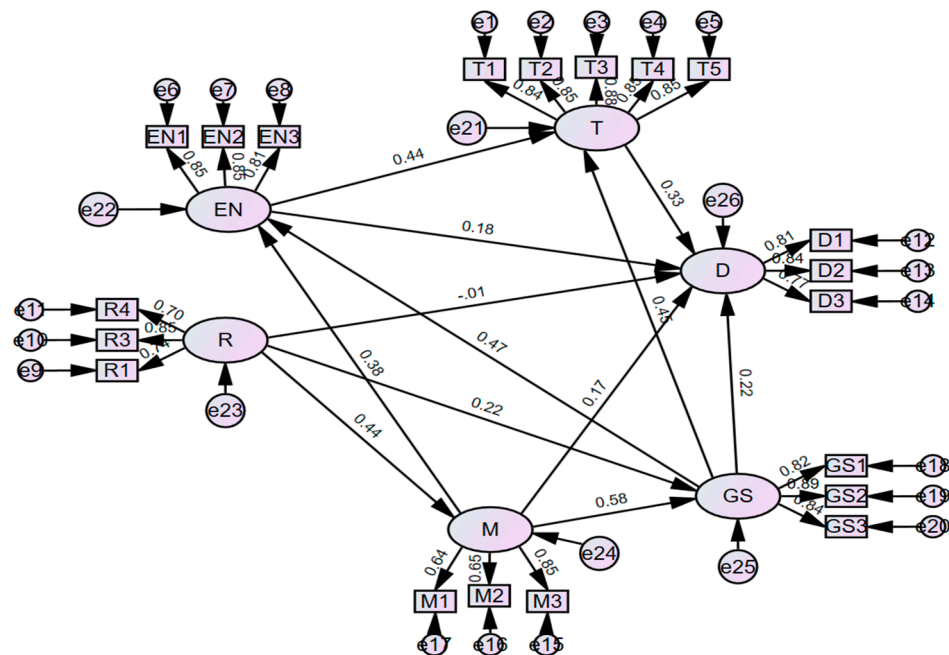


Figure 2. Structural equation model (Significance levels of path coefficients are reported in the subsequent table).

R1, R3, R4, EN1, EN2, EN3, M1, M2, M3, T1, T2, T3, T4, T5, GS1, GS2, GS3, D1, D2, and D3 are the observed variables, and R, EN, M, T, GS, and D are latent variables.

Table 6 reports the standardized factor loadings, AVE, and CR values. The model fit indices in Table 7 demonstrate satisfactory thresholds: GFI, AGFI, IFI, and CFI exceed 0.800, while RMSEA (0.066) and χ^2/df (1.947) fall below critical values of 0.08 and 2.0, respectively. According to Table 7, it can be concluded that all the indicators meet the criteria and partially reach the optimal state, so careful consideration can be used to determine whether the model fit is good [61].

Table 7. Fit index of the model.

Fit Index	Criteria	Value
CMIN/DF	1–3 (Excellent), 3–5 (Good)	1.947
RMSEA	<0.05 (Excellent), <0.08 (Good), <0.1 (Acceptable)	0.066
GFI	>0.9 (Excellent), >0.8 (Acceptable)	0.880
AGFI	>0.9 (Excellent), >0.8 (Acceptable)	0.840
IFI	>0.9 (Excellent), >0.8 (Acceptable)	0.950
TLI	>0.9 (Excellent), >0.8 (Acceptable)	0.939
CFI	>0.9 (Excellent), >0.8 (Acceptable)	0.949
PGFI	>0.5	0.662
PNFI	>0.5	0.750
PCFI	>0.5	0.789

GFI refers to the goodness-of-fit test or the fitness test. The GFI is calculated by the following formula:

$$GFI = 1 - \frac{\hat{F}}{\hat{F}_b} \quad (6)$$

where $\hat{F}$ is the minimum value of the difference function, the F_b by means of the $\sum(n) = 0$, $n = 1, 2, \dots, N$, calculating $\hat{F}_b$. The authors calculated a GFI of 0.880 for the model.

The formula for AGFI is

$$AGFI = 1 - (1 - GFI) \frac{d_b}{d} \quad (7)$$

and included among these is the following.

The model yielded an AGFI of 0.840 and demonstrated acceptable congruence with the empirical dataset. Although structural adequacy was confirmed through multiple indices (GFI, RMSEA, and NFI), most metrics either met or approached established benchmarks (Table 7).

Following rigorous analysis, a robust structural equation framework was developed, aligning with theoretical expectations despite minor threshold variations. The analytical framework integrates path diagrammatic representation (Figure 2) with statistical significance thresholds of parameter estimates (Table 8), with empirical confirmation provided through model fit indices visualization in Figure 3. Hypothesis 2, Hypothesis 4, Hypothesis 5, Hypothesis 6, Hypothesis 9, Hypothesis 10, Hypothesis 12, Hypothesis 13, Hypothesis 14, and Hypothesis 15 were supported but Hypothesis 1, Hypothesis 3, Hypothesis 7, Hypothesis 8, and Hypothesis 11 were not supported.

Table 8. Path coefficients and their significance.

	Path		Std. Est.	S.E.	C.R.	<i>p</i>
M	<---	R	0.444	0.085	5.293	***
GS	<---	R	0.217	0.078	2.851	0.004
GS	<---	M	0.577	0.088	6.619	***
EN	<---	M	0.38	0.098	4.025	***
EN	<---	GS	0.466	0.093	5.155	***
T	<---	EN	0.444	0.081	5.399	***
T	<---	GS	0.446	0.083	5.406	***
D	<---	T	0.331	0.102	3.032	0.002
D	<---	EN	0.175	0.104	1.547	0.122
D	<---	R	−0.014	0.065	−0.203	0.839
D	<---	M	0.172	0.095	1.725	0.084
D	<---	GS	0.224	0.105	2.003	0.045

Note: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

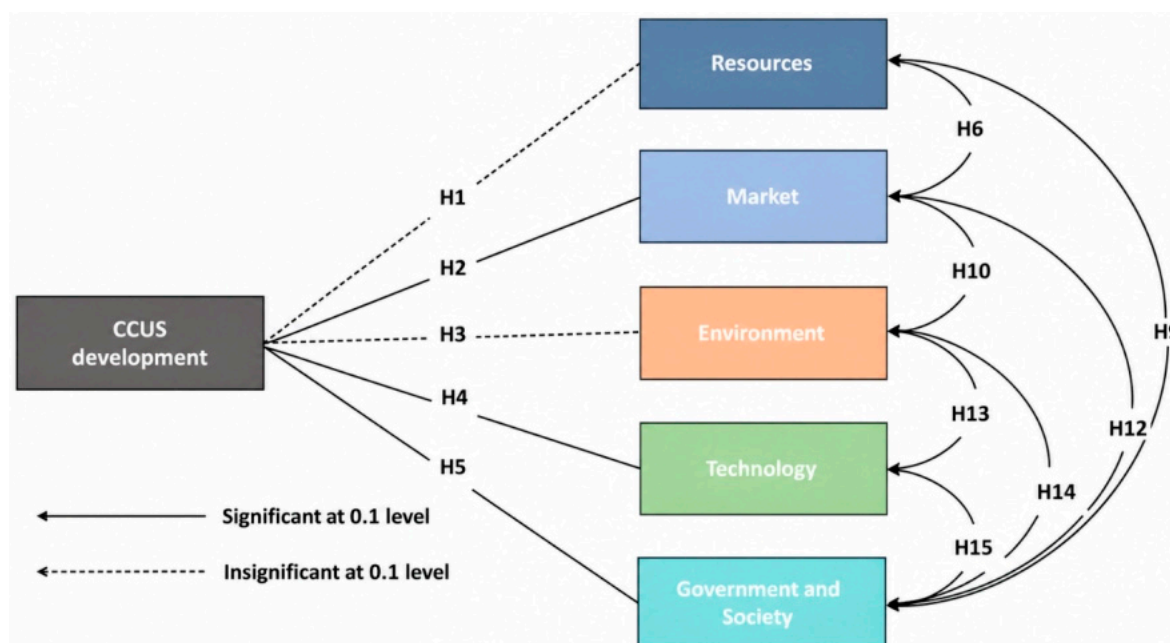


Figure 3. Final theoretical model.

6. Results and Discussion

6.1. Direct Impacts

Structural equation modeling analysis reveals a statistically significant positive association between market dynamics and CCUS advancement ($p = 0.084$), meeting the marginal significance threshold at $\alpha = 0.1$ in covariance-based estimation. H2 is supported; notably, technology and CCUS advancement demonstrate a significant positive correlation ($p = 0.002$), thereby confirming H4. The path coefficient of government and society and CCUS development is positive and significant ($p = 0.045$). Therefore, H5 is supported. To summarize, market, technology, and government and society factors have a direct influence on CCUS. Resource factors and environmental factors have no direct influence on CCUS.

6.2. Indirect Impacts

Iterative testing resulted in removing statistically insignificant indirect effects between four variable pairs: resource–environment, resource–technology, market–environment, and market–technology linkages during model validation. Resources affect markets ($p < 0.001$), and resources affect government and society ($p = 0.004$). Markets will affect government and society ($p < 0.001$), as well as the environment ($p < 0.001$). The environment will influence technology ($p < 0.001$). Finally, it is concluded that resources, environment have an indirect impact on CCUS by influencing markets, technology, and government and society.

6.3. Policy Discussion

Five strategic implications emerge from the findings, tailored to the professional perspectives of the expert sample:

1. Expert-Driven Technological Governance: Leveraging the high path coefficient of technological factors (0.33, Table 8) and experts' specific concerns regarding "CO₂ high-efficiency injection/extraction" (0.88) and "conveying equipment levels" (0.85), policies must prioritize targeted R&D. Governments should establish specialized CCUS technology funds managed by joint university-industry labs to overcome bottlenecks in low-energy absorbents and corrosion-resistant materials. Furthermore, an expert-led "Technol-

ogy Readiness Assessment System” should be developed to standardize key parameters (e.g., CO₂ purity, pipeline pressure) and accelerate the transition from laboratory validation to industrial-scale demonstration.

2. Market Mechanism Optimization: Given the critical role of carbon market maturity (path coefficient 0.85) and experts’ sensitivity to technical costs, market policies require fine-tuning to reduce entry barriers. It is recommended to form a “CCUS Carbon Market Expert Committee” comprising energy economists and environmental policy scholars to design dynamic carbon allowance deduction mechanisms. Additionally, pilot “CCUS Carbon Incentive Schemes” should be launched, providing extra carbon credits for enterprises adopting advanced technologies, thereby aligning financial incentives with the specific cost structures highlighted by the expert sample.

3. Regulatory and Social Integration: To address the strong influence of administrative supervision (0.89) and public risk perception, policy frameworks must be refined through expert consultation. Regulatory standards for ecological risk management should be co-developed by scientific experts to ensure feasibility and effectiveness. Concurrently, leveraging the academic background of the sample, governments should initiate “CCUS Public Engagement Pilot Zones” guided by social science experts, utilizing data from the survey to foster societal acceptance and disseminate best practices for risk communication.

4. Resource Allocation and Infrastructure Planning: Addressing the spatial mismatch between resource endowment and market demand identified by experts (e.g., limited geological space in the east versus water scarcity in the west), governments should commission geological expert teams to develop a “National CCUS Resource Potential Zoning Map.” This map will guide strategic site selection for sequestration. Furthermore, implementing “Cross-Regional CCUS Infrastructure Subsidies” is crucial to support the construction of pipelines connecting western capture sources with eastern utilization markets, thereby resolving logistical inefficiencies caused by geographical disparities.

6.4. Comparison with Existing Empirical Literature

The findings of this research validate the reliability of the proposed CCUS driving framework.

Firstly, regarding methodology, this study employs structural equation modeling (SEM) to decipher the complex relationships within China’s CCUS framework. This approach is consistent with the research tradition established by Kelly [55], who demonstrated that energy consumption is a multi-dimensional issue. Similarly, our model identifies that “Resources” and “Environment” do not always serve as direct drivers for CCUS development; instead, they function as foundational latent variables that shape the market and policy landscape. By quantifying these direct and indirect effects, this paper provides a more nuanced causal map compared to traditional descriptive policy reviews.

Secondly, the identified impact of the “Government and Society” dimension echoes the research conclusions of Wang et al. [62]. Wang et al. emphasized that for high-cost emerging energy technologies, policy gaps and institutional support are the primary “breakthrough” points. Our study confirms that for CCUS, the “Government–Society” factor remains a critical pillar, suggesting that CCUS—much like geothermal energy—requires strong state-led coordination to overcome initial commercialization hurdles.

Furthermore, a comparative analysis of the “Resource” factor reveals the unique industrial characteristics of CCUS. While Zhang et al. [63] identified raw material supply as a direct “dilemma” and bottleneck for China’s bioenergy industry, our results indicate that for CCUS, resource availability primarily influences development indirectly through market mechanisms. This suggests that while bioenergy is highly sensitive to the physical scarcity of biomass, CCUS development is more sensitive to the “economic trans-

formability” of storage resources. This distinction makes our study a valuable reference for understanding the varying levels of resource dependence across different renewable energy sectors.

Finally, our emphasis on social perception within the “Government and Society” construct echoes the consumer-centric findings of Zhang et al. [51] regarding biofuels. Our research highlights that the acceptance of CCUS safety and environmental risks by experts and society is a prerequisite for technological scaling. By integrating these cross-sectoral insights, this article provides a comprehensive empirical benchmark for China’s “dual carbon” strategy, positioning CCUS not merely as a technical tool but as a socio-economically integrated system.

7. Conclusions

The three factors, being market, technology, and government and society, have a significant influence on the development of CCUS in China, with the market factor having an influence of 0.17, the technology factor having an influence of 0.33, and the government and society factor having an influence of 0.22. Among various market-related elements, the developmental maturity of China’s carbon emission trading mechanism demonstrates the most significant path coefficient when measuring its correlation with market forces, with a path coefficient of 0.85. Notably, CO₂ pricing exhibits the strongest structural linkage to market factors (0.65), with oil/gas pricing following closely (0.64), aligning with energy cost dynamics posited in the theoretical framework. As for the technical factors, the path coefficient between the level of CO₂ high-efficiency injection and extraction technology and the technical factor is the largest, with a path coefficient of 0.88; followed by the level of technology of the conveying equipment, the level of technology of the safe production of CCUS-EOR, oil recovery rate of CCUS-EOR is all 0.85; finally, the energy consumption of chemical solvents used for CO₂ absorption has a path coefficient of 0.84. The empirical analysis shows that the strengthening of the administrative oversight system (especially financial incentives such as the CCUS project subsidy scheme) has the strongest path correlation with the institutional variables, with a standardized coefficient of 0.89, under the influence of government and society factor; followed by the path coefficient of the path coefficient between the society’s investment in technology R&D for CCUS projects and this factor is 0.84; and finally, the path coefficient between the investors’ willingness to invest in CCUS (including capital, risk, etc.) and this factor is 0.82. Compared with the technology factor, the market factor and the governmental and social factors have a slightly weaker impact on the development of CCUS in China. This observed disparity could be attributed to the ongoing institutional transition characterizing China’s market-oriented mechanisms, which currently undergo systematic optimization when contrasted with the mature socioeconomic architectures operative in industrialized nations. In the field of CCUS technology, the lack of mature market mechanisms and business models, insufficient market demand for the technology, and the high cost of the technology, which makes investors turn to consider some lower-cost and faster-performance technologies and measures first. For instance, the prioritization of renewables, notably solar and wind energy, has impeded CCUS deployment across China. The Annual Report on China’s Carbon Capture, Utilization and Storage (CCUS) 2023 points out that in order for CCUS technology to play an important role in China’s efforts to achieve the goal of carbon neutrality, it is necessary to build a comprehensive carbon neutral technology system and focus on the research and development of relevant technologies, and the government needs to improve the relevant regulations and standards and formulate targeted incentives, and to strengthen international cooperation and sharing.

Resource and environmental factors exhibit limited influence on CCUS advancement in China, likely attributable to geospatial disparities in viable CO₂ sequestration formations, especially in areas with rapid economic development and high CO₂ emissions, such as the eastern and southern coastal areas, where there is less geologic space suitable for sequestration. The widespread adoption of CCUS technologies faces regional constraints, particularly in water-intensive processes like chemical absorption. While northern and northwestern China grapple with inherent water scarcity, even economically robust eastern regions—despite higher resource availability—encounter competing demands from dense populations and industrial activities. This spatial mismatch between water-dependent CCUS systems and hydrological realities underscores critical infrastructural challenges in scaling decarbonization efforts. In addition, CCUS projects usually require a large number of surface facilities, including capture equipment, transportation pipelines, and injection wells. The cost and technical difficulty of constructing conveyance pipelines increase in densely populated areas with high ground utilization and in areas with mountainous or other complex terrain.

We provide a measurement model from a scholar's perspective based on the above findings. The results and the model are also useful for other stakeholders studying CCUS.

8. Limitations

This study has several limitations that should be acknowledged.

First, regarding the structural equation modeling analysis, the sample-to-parameter ratio is approximately 4.19:1, which is slightly below the conservative guideline of 5:1 [64–66]. A larger sample size would further enhance the robustness of the findings and the generalizability of the conclusions. Future studies are therefore encouraged to collect larger samples to meet stricter statistical criteria for CB-SEM.

Second, the study relies on cross-sectional survey data, which limits the ability to draw causal inferences. Longitudinal designs could help examine the dynamic relationships among the variables over time.

Third, the sample is drawn from a specific context, which may affect the generalizability of the findings to other settings. Future research could include more diverse samples to validate the results across different populations.

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Abbreviations

Abbreviation	Full Name
AGFI	Adjusted Goodness of Fit Index
AMOS	Analysis of Moment Structures
AVE	Average Variance Extracted
BECCS	Bioenergy with Carbon Capture and Sequestration
CFI	Comparative Fit Index
CFA	Confirmatory Factor Analysis
CR	Construct Reliability
CCUS	Carbon Capture, Utilization, and Storage
DACCS	Direct Air Capture and Carbon Storage
EOR	Enhanced Oil Recovery
GFI	Goodness of Fit Index
IEA	International Energy Agency
IFI	Incremental Fit Index
IPCC	Intergovernmental Panel on Climate Change
KMO	Kaiser–Meyer–Olkin
LCA	Life Cycle Assessment
NFI	Normed Fit Index
PCFI	Parsimony Comparative Fit Index
PGFI	Parsimony Goodness of Fit Index
PNFI	Parsimonious Normed Fit Index
QR code	Quick Response Code
R&D	Research and Development
RMSEA	Root Mean Square Error of Approximation
SEM	Structural Equation Modeling
SPSS	Statistical Product and Service Solutions
TLI	Tucker–Lewis Index
TRLs	Technological Readiness Levels
UNFCCC	United Nations Framework Convention on Climate Change

Appendix A

Table A1. Questionnaire measurement items.

Variable	Measurement Item	References
Resources (R)	R1: I think the higher CO ₂ concentration is more favorable to the nationwide proliferation of CCUS in China.	[28,39,41]
	R2: I believe that the CO ₂ phase state (the phase state includes gas, liquid or solid) is A significant contributor that restricts the nationwide proliferation of CCUS in China.	[39]
	R3: I think the higher CO ₂ purity is more favorable for the large-scale development of CCUS in China.	[30,39]
	R4: I think the more complete China's gas supply system is, the more favorable it is for the nationwide proliferation of CCUS in China.	[8,32]
	R5: I believe that China's CO ₂ reserves (CO ₂ reserves refer to the total amount of CO ₂ in underground reservoirs that can be permanently sequestered, including CO ₂ in natural gas and oil reservoirs, CO ₂ in coal reservoirs, and underground saline formations, etc.) meet the basic conditions for nationwide proliferation of CCUS.	[14,36,42]

Table A1. Cont.

Variable	Measurement Item	References
Environment (EN)	EN1: I think the maturity of CO ₂ transportation technology will benefit the development of CCUS.	[8,32]
	EN2: I think CO ₂ absorption of solvent residues poses a serious pollution problem.	[30]
	EN3: I think the maturity of CO ₂ sequestration technology will be favorable to the development of CCUS.	[36,49]
Market (M)	M1: I think the higher the price of oil and gas, the more favorable it is to increase the motivation of Chinese CCUS developers.	[43,46]
	M2: I think the higher the price of CO ₂ , the more favorable it is to increase the motivation of Chinese CCUS developers.	[43,47]
	M3: I think the more mature the Chinese carbon market becomes, the more favorable it is for the development of CCUS in China.	[44,45,47]
Technology (T)	T1: I think the lower the energy consumption of the chemical solvents used for CO ₂ absorption the better for CCUS development.	[30,35]
	T2: I think the higher the level of conveyor technology the better for CCUS development.	[32]
	T3: I think the higher the level of CO ₂ efficient injection and extraction technology the more favorable it is for CCUS development.	[33,34,40]
	T4: I think the higher the level of safety production technology in CCUS-EOR the better for CCUS development.	[33,34,36]
	T5: I think the higher the oil recovery from CCUS-EOR the better for CCUS development.	[33,34,39]

Table A2. Questionnaire measurement items (continued).

Variable	Measurement Item	References
Government and Society (GS)	GS1: I believe that investors' willingness to invest in CCUS (funds, risks, etc.) influences the advancement of CCUS deployment in China.	[48,50]
	GS2: I believe that the regulatory frameworks governing public sector oversight (subsidy policies, etc.) for CCUS deployment is conducive to the advancement of CCUS in China.	[22,25,48]
	GS3: I believe that social support for technological research and development of CCUS projects is beneficial for the development of CCUS in China.	[22,48]
CCUS Development (D)	D1: I think the CCUS program is going to get better and better in China.	[4,5,26,27]
	D2: I think the CCUS system will get better in the next 5 years.	[48,50]
	D3: I think the development of the CCUS program can reduce China's CO ₂ emissions.	[22,25,48]

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