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Research Article

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A Review of CCUS Development in China: Technological Progress, Policy Challenges and Commercialization Opportunities

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Abstract

CCUS is considered one of the key pillars of China's dual-carbon objectives and has emerged as a vital mechanism to facilitate decarbonization of the power generation and the energy-intensive industrial sector, as well as emerging sectors within China. To that end, this paper summarizes relevant literature related to CCUS both technical and policy recent developments in the CCUS landscape in China, bottlenecks that may be encountered near term through the capture, transport, storage and utilization components of CCUS, and provides approaches to close the demonstration to commercialization gap. This includes an examination of the technologies associated with carbon capture and their integration with power and industrial systems in China (including post-combustion, pre-combustion, and oxy-fired combustion) and the infrastructure for transporting and storing CO2 (including pipelines, ships, offshore options, and regional hubs), the methods of storing CO2 (including geological, mineralization, and marine storage), and the methods of utilizing CO2 (including CCU, BECCS, and DAC) in relation to the policy, market and governance environments in China. Key enablers of CCUS that are identified and discussed in this paper include CCUS industrial clustering, shared CO2 transport/storage hubs, data-driven surveillance and monitoring, and China-specific financial instruments that are designed for use by domestic institutions. This paper also discusses the variability between different regions of China in terms of policy maturity, financial appetite, and infrastructure preparedness, where there are differing views of maturity, economics, or governance, we identify such inconsistencies and assess potential implications to strategy development. Finally, we present research agendas and considerations for policy development that would facilitate the acceleration of the commercialization of CCUS in China, including an emphasis on industrial cluster deployment, having strong MMV protocols in place, and utilizing market instruments to ensure that CCUS efforts will assist in supporting the achievements of the long-term national decarbonization goal.

Keywords: CCUS China, Commercialization, Industrial Clusters, MMV, Policy, Finance

1. Introduction

The development of carbon capture, utilization and storage (CCUS) has become a vital component of China's decarbonization strategy, with a strong focus on the integration of CCUS into coal-based power generation, along with steel, cement, and chemical production; and on potential Negative-Emissions Technologies (NETs) pathways. The existing literature has regularly indicated that while CCUS capture technologies are technically viable at the pilot level, they are not being widely implemented at the commercial scale in China due to high costs, gaps in required infrastructure, the lack of clear regulations, and uncertainty regarding risk-sharing throughout the entire value chain [1-3]. The literature shows that the pathway from demonstration to commercialization which involves appropriate policy design, dedicated financing, and requisite infrastructure will remain necessary for achieving both learning-based cost reductions and scale effects for aggregate carbon dioxide (CO2) emissions captured, transported, and stored [1,3,4]. The scope of this project will include capture technologies (post-combustion, pre-combustion, or oxy-fuel), transportation and logistics planning, geological and mineralization methods for CO2 storage, as well as utilization options (i.e., developing usable products from captured CO2), and will be analyzed within the context of China's changing policy mechanisms and institutional frameworks [5-8].

2. Methodology

In this literature review on the rollout of CCUS in China looks at both national and international research on how CCUS is developing in the country. It also draws on reports and policy frameworks published by the Chinese government. The review makes an effort to connect China-specific findings to official policy documents, including national strategies, Five-Year Plans, and sector-focused roadmaps. It also incorporates peer-reviewed studies that examine CCUS in China [1,3,4,9]. Overall, the review provides a thorough analysis of key themes in CCUS development, including how clusters form, how Monitoring, Measurement, and Verification (MMV) regulations are defined, and what financing strategies are used. It highlights that building CCUS clusters in industrial areas supports shared infrastructure, strengthens regional cooperation, and enables hub-and-spoke or multi-emitter setups.At the same time, MMV systems help establish consistent regulatory and reporting structures for monitoring and verifying CO_2-related activities. In addition, the review identifies multiple financing approaches such as government funding, support for demonstration projects, carbon pricing policies, financial incentives, and new market-based solutions as critical drivers for speeding up CCUS deployment and moving it toward commercialization. The review also notes that CCUS implementation varies by region across China as shown in Figure 1 [1,4,10].

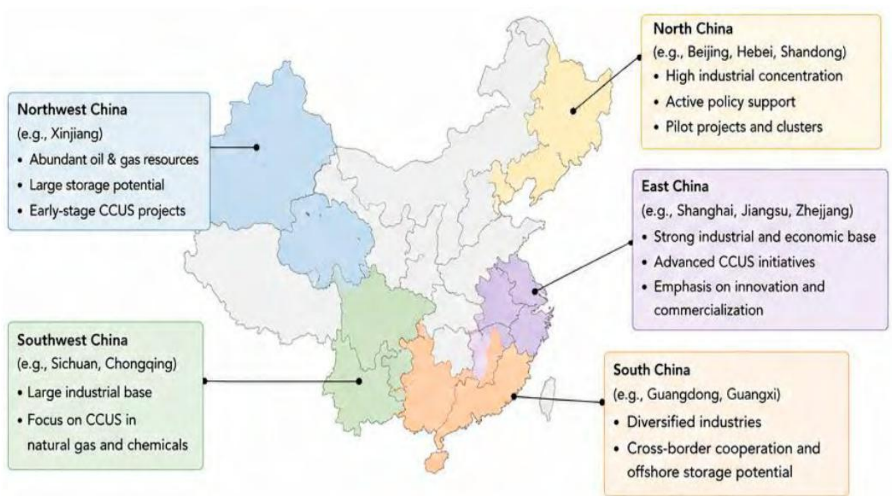

Figure 1: Reorganizing Regional Differences in CCUS Implementation Across China

3. Technological Landscape in China: Capture, Transport, Storage, And Utilization Capture Technologies

Post-combustion capture (PCC) is the dominant technology for the retrofit of existing coal-fired power plants and many new coal-fired power plants in China. There are several strategies underway to reduce the energy penalties, solvent costs, and complexity of integrating PCC systems with China's unique power system configurations. The literature identifies two key cost drivers associated with the deployment of PCC technologies in China: energy intensity and solvent management; therefore, it is necessary to develop new processes and materials that can facilitate the large-scale deployment of PCC retrofits in China [3,6,11]. Pre-combustion capture and oxy-fuel combustion represent complementary paths for integrating capture technologies, with the literature showing proof of concept in energy penalty reductions through heat integration and optimizing cycles by improving performance metrics. There are examples of regional leaders demonstrating successful pilot projects for capture deployment; however, adoption rates remain inconsistent throughout China [6,7]. The potential for significant energy savings exists for reactive separation and process intensification coupled with capturing and recovering useful energy through advanced power cycles; however, near-commercial demonstration is required to validate techno-economic (TEA) and life-cycle assessment (LCA) implications for China [5,12,13].

3.1. Transport and Storage Infrastructure

The deployment of CCUS technology across China has experienced delays because of the availability of transport and storage infrastructure (pipelines and maritime options). Industrial clusters are developing alongside coal-power corridors and regional hubs; therefore, storage site characterization, long-term monitoring and liability frameworks are the primary factors that influence project risk and public acceptability in China. Shared hubs and cross-regional pipelines have the potential to create economies of scale; however, to achieve such economies, regulatory frameworks, financing models, and governance agreements must be harmonized for regional CCUS clusters [14-16]. Additionally, concepts for offshore transporting carbon dioxide and cross-border transporting carbon dioxide have been proposed to support coastal-inland integration by aligning policies and securing financing arrangements that mitigate the risk associated with large-scale regional deployments of CCUS [12,17-19].

3.2. Utilization and NETs

The use of CO2 through a variety of ways, including CCU options, along with negative-emitting technologies like Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS), are becoming more explored and studied in China according to Chinese publications. While these pathways provide revenue and emissions offset opportunities, there is still concern about their energy intensity, lifecycle impacts, and well-developed markets for CO2-derived products in China. Researchers are developing TEA/LCA frameworks specific to Carbon Capture and Utilization (CCU) applications in China to assist in decision making and ensure criteria for sustainability within the cement, steel, and chemical sectors [3,5,8,15].

3.3. System-Level Integration and Innovation Pathways

A central theme involves transitioning from single-project demonstrations to integrated carbon capture, use and storage (CCUS) clusters which utilize shared capture, transportation, and storage facilities to promote both learning through doing and economies of scale. Concepts such as regional hubs and cross-border clusters can be viewed as valuable instruments for advancing the deployment of CCUS provided that there is sufficient alignment between the regulatory and financing frameworks. The TEA/ LCA guidance for CCU in China seeks to establish standardized methodologies for evaluating CCU projects to create comparability across projects and provide relevant information for making investment decisions in the context of a constantly changing policy environment, Integration of carbon capture with hydrogen, bioenergy and digital optimization will likely dictate future deployment patterns and related policies in China over the next 10 years [5,8,20,21]. The overview technological landscape in China is illustrated in Figure 2.

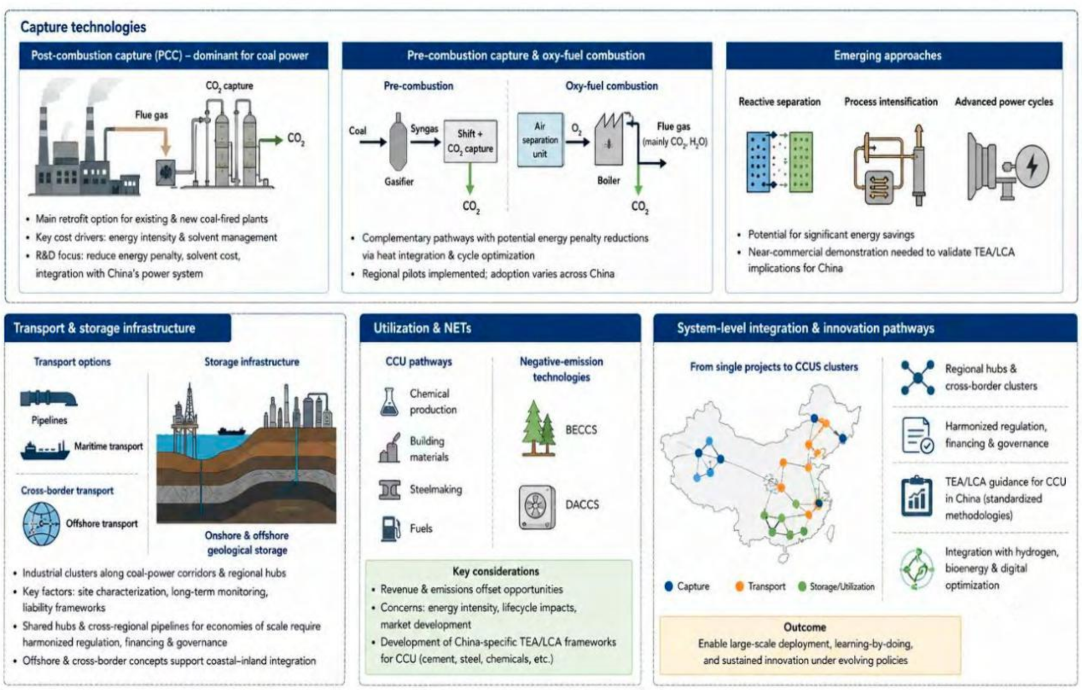

Figure 2: Technological Landscape in China: Capture, Transport, Storage and Utilization

4. Policy, Economics, Governance: The Commercialization Gap in China

4.1. Commercialization Gap and Policy Design

Analyses have identified that there is a commercial gap caused by the lack of alignment between the ability to do pilot demonstrations and the ability to deploy at scale due to the need for upfront capital for infrastructure and the existence of policy barriers. Policy in China for CCUS is composed of four types of policies, including: (1) central planning, (2) pilot demonstration programs, (3) industrial policy, and (4) emerging market mechanisms. Financing is emphasized through the establishment of support programs in combination with reducing Capital

Expenditure (CAPEX) and Operating Expenditure (OPEX) and establishing dedicated CCUS demonstration pipeline programs. From an innovation-system perspective, coordinated governance networks and multi-stakeholder collaboration are needed to support the commercialization of CCUS and various policy instruments to align incentives through the CCUS chain; however, only delivering improvements in technology does not guarantee commercialization through the market without further supportive governance and design of the market [1,4,15].

4.2. Economics, Financing, and Risk

The economic barriers of CCUS in China are primarily due to capture costs, energy penalties, and storage liabilities. As a means of reducing costs through economies of scale, learning, and integration, carbon pricing (where imposed) or policy incentives will be required to generate private funding for CCUS. The financial dynamics in China point out that CCUS will require robust business models, integrated infrastructure planning, and risk-sharing with the public sector in order to attract private investment. In a similar vein, the maturity of policies and design of regional markets will determine the speed of project deployment and be a factor in the level of risk that exists between the different regions in China [14-16,19,21].

4.3. Regulation, Liability, and Public Acceptance

Having clear regulations on what happens after a site has been used to store CO_2 is very important when trying to bring in money to put into transporting and storing CO_2 in China. Public acceptance will also be a barrier to people supporting offshore and cross-border CCUS projects. Public engagement and information about risks related to these types of projects are required [1,22,23].

4.4. Sectoral and Regional Policy Instruments

China's CCUS policy landscape comprises national plans, pilot programs, sector-specific roadmaps, and evolving market mechanisms to support CCUS deployment. Sector-specific policy design for cement, steel, and power sectors remains critical to tailor deployment pathways, craft demonstration-to-commercialization roadmaps, and align CCUS with domestic industrial policy and energy-transition objectives [6,7,11,24]. Table 1 summarizes the major findings from the reviewed literature regarding CCUS commercialization and policy development in China.

Section	Key Theme	Main Findings from Literature	Key Challenges Identified	Policy / Strategic Implications	References
Commercialization gap and policy esign	Commercialization gap	Studies identified a gap between successful pilot demonstrations and large-scale CCUS deployment in China due to high upfront infrastructure costs and policy barriers.	Limited infrastructure investment, insufficient market incentives, fragmented policy alignment, and difficulty scaling projects beyond demonstrations.	China's CCUS policy framework relies on central planning, pilot programs, industrial policy, and emerging market mechanisms. Stronger governance coordination and incentive alignment across the CCUS chain are needed to support commercialization.	Mollahosseini et al.[5];; Ruttinger et al. [4]; Tota et al. [15];
	Financing and innovation systems	Financing strategies emphasize reducing Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) while supporting demonstration pipeline programs.	Technology improvements alone are insufficient to ensure market commercialization without governance and supportive market design.	Coordinated governance networks and multi-stakeholder collaboration are essential to accelerate commercialization and investment confidence.	Mollahosseini et al. [5]; Ruttinger et al. [4];)
Economics, financing, and risk	Economic barriers	Major economic barriers include high capture costs, energy penalties, and long-term storage liabilities.	High operational costs, uncertain revenue streams, and investment risks discourage private-sector participation.	Carbon pricing mechanisms and policy incentives are necessary to mobilize private investment and reduce financial uncertainty.	Pieri et al. [6]; Tota et al. [15]
	Business models and infrastructure planning	CCUS deployment requires integrated infrastructure systems and robust business models supported by public-private risk sharing.	Weak market maturity and regional policy inconsistencies increase investment uncertainty across China.	Regional policy development and integrated planning are critical to accelerating CCUS deployment and reducing investment risk.	Update of the Roadmap for Carbon Capture, Utilization, and Storage Demonstration and Deployment in the People's Republic of China [14];

Regulation, liability, and public acceptance	Regulation and liability	Clear post-closure liability regulations for CO_2 storage sites are necessary to encourage investment in transport and storage infrastructure.	Regulatory uncertainty regarding long-term storage responsibility and liability management.	Establishing transparent legal and regulatory frameworks can improve investor confidence and project development.	Wei et al. [1]; Zauner et al. [23]
	Public acceptance	Public support is considered a major factor influencing offshore and cross-border CCUS deployment.	Limited public awareness and concerns regarding environmental and safety risks.	Public engagement initiatives and transparent communication about project risks are required to improve social acceptance.	Wei et al. [1] Pieri et al. [6]; Rimbono & Koestoer [7]; Mikulčić et al. [24];
Sectoral and regional policy instruments	Sectoral policy instruments	China's CCUS policy landscape includes national plans, pilot projects, sector-specific roadmaps, and evolving market mechanisms.	Deployment pathways differ significantly across industrial sectors and regions.	Tailored policies are needed for cement, steel, and power sectors to align CCUS deployment with industrial and energy-transition goals.	Wei et al. [1] Pieri et al. [6]; Rimbono & Koestoer [7]; Mikulčić et al. [24];
	Regional implementation differences	Regional market maturity and policy design strongly influence the speed and scale of CCUS deployment across China.	Uneven policy implementation and varying economic conditions between regions.	Regional coordination and locally adapted policy frameworks are necessary to support balanced CCUS commercialization nationwide.	Wei et al. [1]; Ruttinger et al. [4]; Mollahosseini et al. [5]

Table 1: Literature Review of Policy, Economics, Governance and Commercialization Gap in China

5. Strategic Pathways from Demonstration to Commercialization in China

5.1. Pathway 1: Build Industrial Clusters and Shared Infrastructure

Integrated industrial clusters facilitate the supply of carbon capture, transport and storage infrastructure; therefore, deploying CCUS across these integrated industrial clusters will allow China to capture economies of scale while simultaneously diversifying their risk. China can also leverage regional CCUS hubs and transnational pipelines that facilitate CCUS deployment; however, these benefits will depend on their ability to successfully create risk-sharing governance systems and accessible financing structures that encourage long-term investment stability [1,17,18,20].

5.2. Pathway 2: De-Risk with Policy and Financing Alignment

A combination of carbon pricing (in regions that implement it), performance-based subsidies, public funding for early-stage projects, and financing instruments with long repayment periods can help to commercialize technologies. In order to attract investment capital into commercialization of these technologies' references are made to the need for regulatory certainty on MMV values, storage liabilities, and rights-of-way for transportation pipelines; creating regional demonstrational projects will help to mobilize private investments and expedite project seasoning to become bankable [1,6,15,17].

5.3. Pathway 3: Accelerate Capture Cost Reductions Through R&D and Integration

By integrating energy recovery/energy use with process intensification, new materials, and reactive separation concepts, it is possible to decrease both capital expenditure and energy consumption penalties. The integrated capture-transport-transfer-utilization of CO2 in clusters should also use TEA/LCA benchmarking to quantify the benefits of the integrated technology and decrease developer/performance/developer risk in China [1,5,8,13].

5.4. Pathway 4: Align CCUS With Decarbonization and Energy-System Goals

The careful policy structure that governs how to consider land use and energy needs, and the trade-offs between different types of emissions (i.e., NETs, BECCS and DACCS) is critical to support a strong and effective negative-emissions pathway. Negative-emissions technologies such as BECCS and DACCS can play an important role in helping China achieve its decarbonization goals and create a stable market for both renewable energy sources and for those sources that rely on CCUS, hydrogen, or improved supply chain processes, and ultimately, result in a more sustainable economy [1,24-26].

5.5. Pathway 5: Foster Governance, Data, and Monitoring Ecosystems

In China, scalable CCUS deployment needs to be driven by data (MMV), evaluated and improved through digital monitoring and optimization. Transparency and investor confidence will be improved through shared data standards and publicly available registries and performance dashboards. Governance arrangements and stakeholder engagement will facilitate the acceptance of projects and their deployment speed [1,8,20,27]. Figure 3 illustrates five integrated pathways for accelerating large-scale CCUS commercialization in China, including industrial cluster development, policy and financing alignment, capture cost reduction through research and development (R&D), integration with decarbonization and energy-system goals, and the establishment of governance, monitoring, and data ecosystems. The framework highlights the importance of shared infrastructure, supportive policies, technological innovation, MMV systems, and stakeholder collaboration in supporting China's long-term carbon neutrality and sustainable industrial transition objectives.

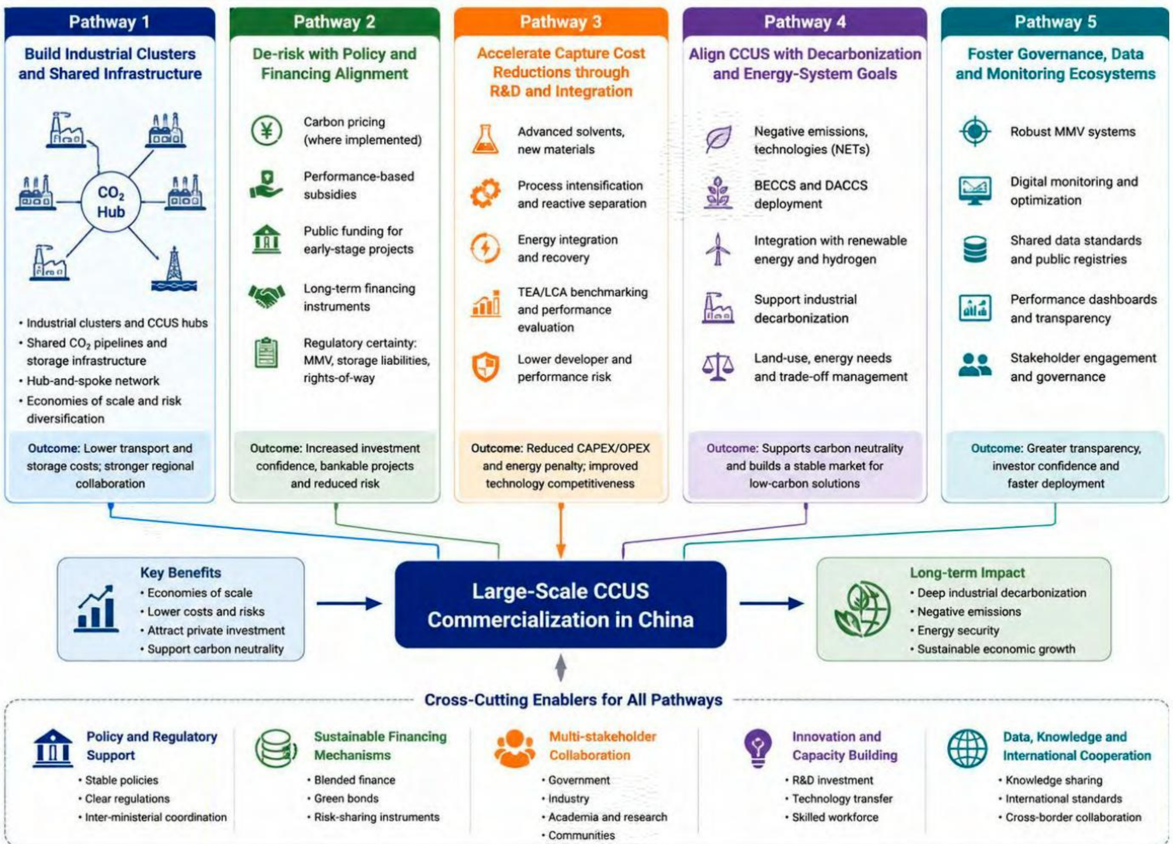

Figure 3: Strategic Pathways for Transitioning CCUS From Demonstration to Commercialization in China

6. Discussion: Nuances and Debates

There is a recurring theme of technological maturity compared to equipment on deployment: Several different forms of captured carbon can reach pilot/demonstration scale, whereas others will require additional demonstrations to establish Technology Economic Assessment/ Life Cycle Analysis implications for scale-up in China; this is also evident by the unevenness of both Policy Maturity and Deployment Plan timelines across Coastal vs. Inland Provinces, leading to regionalized requirements for roadmaps and harmonized standards [1,6,7,14,19]. DAC and CCU pathways provide long-term decarbonization potential but impose energy costs and policy challenges; near-term demonstrations with clear policy signals are encouraged to spur investment, while managing expectations regarding market development [1,24,26]. Figure 4 illustrates the major technological, policy, and regional challenges associated with scaling CCUS deployment in China.

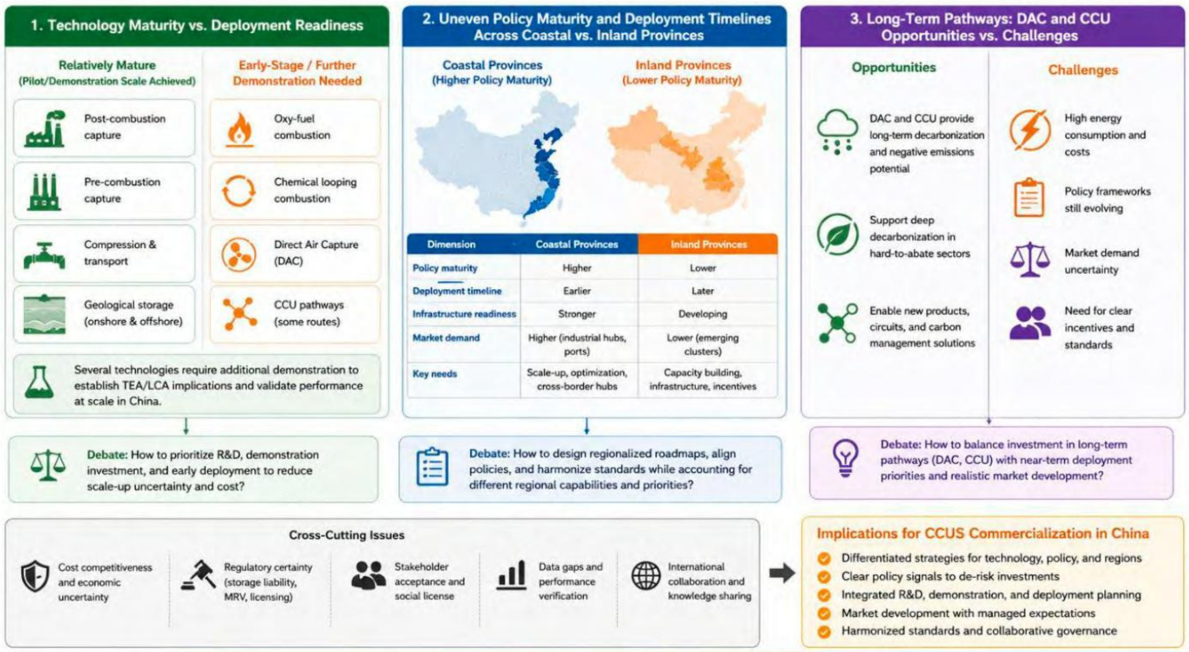

Figure 4: Nuances and Debates in Advancing CCUS Commercialization in China

7. Conclusion

China is now at a crucial crossroads. Coordinated cluster-based CCUS deployment underpinned by policy and finance alignment; rapid Research and Development (R&D); and alignment with broader decarbonization strategies represent an attractive path to large-scale CCUS commercialization. The evidence suggests a multi-faceted strategy, consisting of integrated demonstration projects across industrial clusters; long-term policies and financing to reduce the risk of early-stage projects; and increased capture cost reductions through innovation in materials and process intensification. Additionally, governance frameworks will be necessary to ensure TEA/LCA comparability and sustainability throughout the CCUS value chain. Regional diversity will continue to exist within China; however, an integrated pathway, aligned with China's national decarbonization targets and relying on robust MMV and data-sharing (DS) ecosystems, will be critical for CCUS development in China [28-45].

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