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From Innovation to Integration: The Evolving Role of Carbon Capture and Storage in Global Decarbonization

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ABSTRACT

Carbon capture and storage (CCS) has evolved from a conceptual mitigation option into a cornerstone of global decarbonization strategies. This review provides a comprehensive synthesis of CCS's technological, intellectual, and institutional evolution, emphasizing its transition from isolated engineering applications to system-wide integration. Drawing on a bibliometric analysis of more than 19,000 publications (2001–2025) from the Web of Science Core Collection visualized through CiteSpace, we map the global research landscape and reveal the field's thematic shift from capture and sequestration processes toward integrated approaches that couple CCS with hydrogen, bioenergy, and digital optimization frameworks. Technologically, CCS has advanced through three primary pathways—post-combustion, pre-combustion, and oxy–fuel combustion—each with distinct capture mechanisms, energy penalties, and retrofit potentials. At the deployment level, CCS expansion remains geographically uneven: industrialized economies such as China, the United States, and the United Kingdom dominate operational capacity, whereas emerging and developing economies face barriers related to infrastructure, financing, and governance. By integrating bibliometric, technological, and comparative analyses, this review develops a multidimensional framework encompassing policy design, institutional capacity, and deployment structure. The findings highlight that CCS's future effectiveness depends not only on technological efficiency but also on coordinated governance, cross-border storage networks, and its alignment with broader innovation ecosystems driving the global net-zero transition.

1 | Introduction

The intensifying urgency of the climate crisis has catalyzed a global reconfiguration of decarbonization strategies, particularly in sectors characterized by high emissions and limited alternatives. As the window to achieve net-zero narrows, carbon capture and storage (CCS) has resurfaced as a potentially indispensable pillar of mitigation policy [1, 2]. Although historically sidelined in favor of more politically palatable solutions such as renewable energy, CCS is now being repositioned as a complementary infrastructure capable of addressing residual emissions across power generation, heavy industry, and hydrogen production [3, 4]. The shift is especially pronounced in jurisdictions advancing legally binding climate targets, carbon contracts for difference, and sector-specific roadmaps. However, the renewed momentum around CCS is shadowed by contentious debates about its effectiveness, legitimacy, and long-term strategic value.

In recent years, the CCS landscape has expanded rapidly in scope and ambition. According to the Global CCS Institute, the number of projects in the global pipeline has surged from 135 in 2021 to more than 600 by 2024 [5]. These include a growing number of operational facilities and pilot programs spanning not only coal- and gas-fired power but also hydrogen production, cement, chemicals, ethanol, and biomass energy [6]. This diversification signals an important evolution: from a narrowly defined carbon removal option to a broad enabling platform for hard-to-abate sectors [7, 8]. Yet, the expansion is geographically uneven, concentrated in a small subset of countries—primarily the United States, Canada, the United Kingdom, Norway, and Australia—where enabling conditions such as policy support, industrial capacity, and stakeholder alignment have coalesced [9]. In contrast, emerging economies and lower-income countries have struggled to move beyond feasibility studies, constrained by institutional fragmentation, capital scarcity, and weak regulatory architectures [10].

Despite the proliferation of pilot projects and commercial deployments, a number of structural barriers continue to undermine the scalability of CCS. These include persistently high capital expenditures, uncertain long-term revenue streams, inadequate liability frameworks, and fragmented permitting regimes [11]. Public skepticism, particularly when CCS is deployed by fossil fuel incumbents, further complicates the social license to operate [12]. Critics warn that CCS could serve as a technological fig leaf, enabling the prolongation of fossil fuel infrastructures without delivering meaningful climate benefits. At the same time, proponents argue that certain sectors, such as cement, steel, and chemicals, have no viable decarbonization pathway without CCS [13, 14]. This fundamental tension between technological necessity and institutional feasibility has yet to be resolved in the literature, where assessments often remain siloed in either technical or policy dimensions.

To address this analytical gap, this review adopts a multidimensional systems perspective that integrates quantitative bibliometric evidence with comparative policy analysis. Using more than 19,000 publications (2001–2025) from the Web of Science Core Collection visualized through CiteSpace, we first map the global research landscape and intellectual evolution of CCS studies. Building on these insights, we develop a comparative framework encompassing policy design, institutional capacity, and deployment structure to examine national CCS strategies and their implementation pathways. Using this framework, we classify countries into three distinct clusters: (i) high-capacity industrialized countries with advanced CCS ecosystems, (ii) resource-rich economies deploying CCS as a strategic hedge, and (iii) capacity-constrained or low-income countries with minimal or symbolic deployment. This review then traces how technological innovation, industrial diversification, and system integration have jointly shaped the evolving role of CCS in global decarbonization. The final section explores future pathways for system-wide integration, highlighting the coevolution of CCS with innovation ecosystems, cross-border infrastructure, and complementary low-carbon technologies. By bridging technical performance with political economy insights, this review offers a comprehensive synthesis that informs both scholarly debates and policy design.

2 | Evolution of CCS Technologies and Research Paradigms

CCS technology has emerged as a critical approach to mitigating climate change by capturing CO_2 emissions from industrial sources and storing them safely to prevent release into the atmosphere [15]. Over the decades, CCS has evolved through several phases, marked by groundbreaking milestones, technological innovations, and large-scale projects [16]. The progression of CCS technology reflects a growing global emphasis on reducing greenhouse gas emissions and achieving net-zero targets, driven by policy incentives, industry collaboration, and scientific advancements. To trace the intellectual evolution and collaborative dynamics of CCS research, bibliometric data were retrieved from the Web of Science Core Collection in October 2025. The topic query "carbon capture and storage" was applied to titles, abstracts, author keywords, and keywords plus, returning more than 20,000 records from 2001 to 2025. After manual screening to remove duplicates and irrelevant entries (e.g., unrelated CO_2 utilization studies or nontechnical policy commentaries), 19,222 valid publications were retained for analysis. These records encompass peer-reviewed journal articles, reviews, and conference proceedings across environmental science, engineering, and policy domains. Bibliometric visualization and network analysis were conducted using CiteSpace to uncover the structural and temporal patterns of CCS research [17, 18]. Specifically, Figure 1 presents the overall publication trend and geographical distribution of CCS-related publications; Figure 2 visualizes keyword co-occurrence patterns, and Figure 3 illustrates the temporal evolution of research frontiers based on burst detection analysis; Figure 4 shows the national collaboration network, highlighting major contributing countries; Figure 5 maps the institutional collaboration network. Together, these figures provide a systematic overview of the CCS knowledge landscape and its dynamic development over time.

Although the technological evolution of CCS can be traced back to 1972, when the earliest conceptual and pilot-scale studies appeared, the bibliometric analysis in this study begins in 2001 for reasons of data quality and methodological consistency. Before the early 2000s, CCS-related publications in major indexing databases (such as the Web of Science Core Collection) were sparse, inconsistently classified, and often embedded within broader chemical engineering or energy research categories, making trend analysis and keyword network construction unreliable. From 2001 onward, however, CCS emerges as a clearly defined research domain, with standardized terminology (e.g., "carbon capture," "CO_2 storage," and "CCS technology") and stable indexing practices after the launch of industrial demonstration projects and international initiatives. Therefore, the 2001–2025 bibliometric window provides the earliest period in which publication trends, research clustering, and knowledge evolution can be systematically and comparably assessed. Additionally, the bibliometric record (2001–2025) effectively captures the second and third phases of CCS development, as summarized in Table 1: (i) the industrial scaling stage (1996–2009), marked by growing international research output and pilot deployment, and (ii) the integration and commercialization stage (2010–present), characterized by interdisciplinary convergence and system-level innovation.

Consequently, the CiteSpace-based analysis quantitatively complements the historical and technological narrative by showing how global collaboration networks, institutional structures, and thematic focuses evolved alongside the

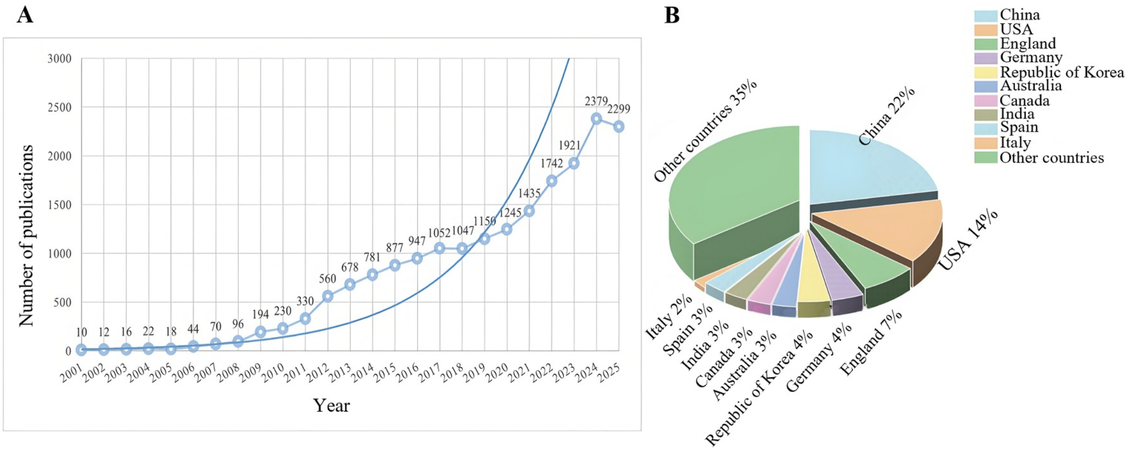

FIGURE 1 | Publication trends and global contributions of CCS. (A) Publication trends of CCS. The solid line represents the actual annual number of publications, whereas the dotted line indicates the fitted exponential growth trend, highlighting the accelerating academic interest and the expansion of the CCS research domain in recent years. (B) Geographical distribution of CCS-related publications, showing that research output is dominated by China (22%), followed by the United States (14%) and England (7%). The remaining contributions are more evenly distributed among other countries, indicating the global yet regionally concentrated nature of CCS research.

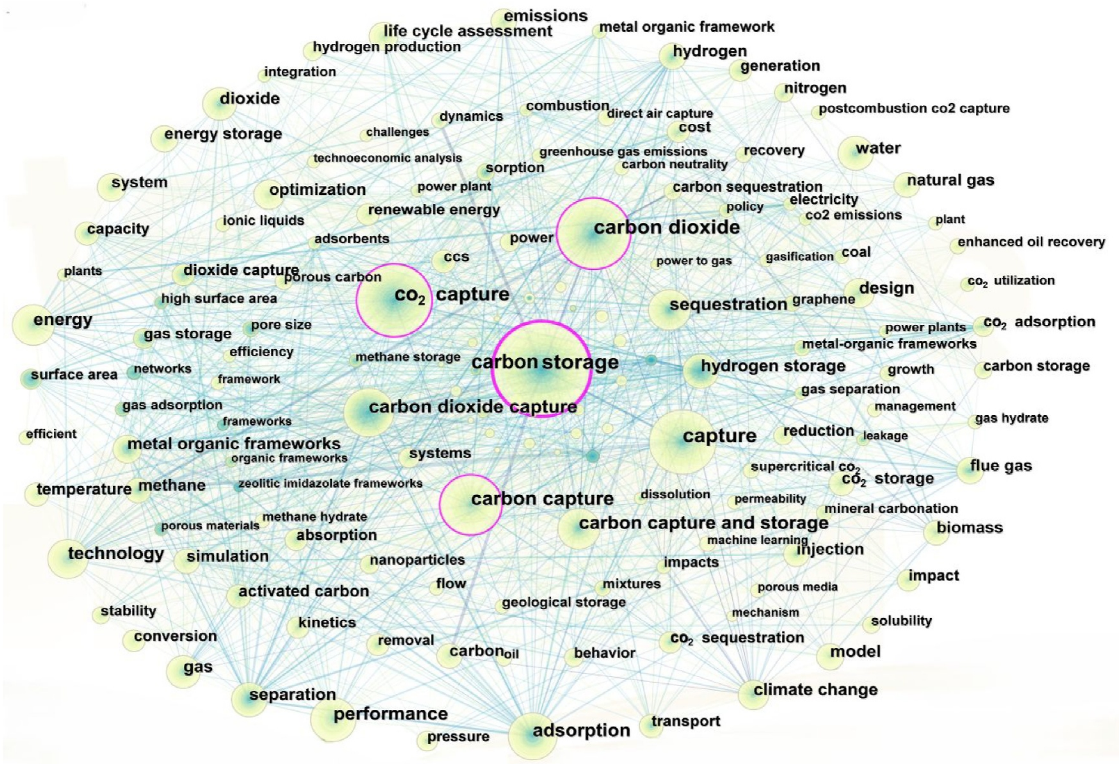

FIGURE 2 | Keyword co-occurrence network (2012–2025). Each node represents a keyword, with node size indicating frequency and link thickness denoting co-occurrence strength. The color gradient reflects the average publication year of each keyword, following the standard CiteSpace time-slicing scheme in which warmer colors (yellow–orange) indicate more recent research (2020–2025), green represents mid-stage topics (2016–2019), and cooler colors (blue–cyan) correspond to earlier themes (2012–2015). This color scheme is identical to the temporal legend shown in Figure 3, where the full year–color mapping is explicitly displayed.

progressive maturation of CCS technology since its conceptual inception in the 1970s. To complement the bibliometric insights with a historical perspective, the following section outlines the three developmental phases of CCS, from its conceptual and pilot beginnings in the 1970s to the current stage of large-scale integration and commercialization.

2.1 | Early Exploration Phase (1972–1995)

The early exploration phase of CCS technology laid its conceptual and practical foundations [19]. During this period, the technology primarily focused on using CO_2 for enhanced oil recovery (EOR), whereas researchers explored its potential for

FIGURE 3 | Temporal evolution of research hotspots (2012–2025). Early bursts relate to capture technologies and geological storage, whereas recent bursts emphasize integration, digitalization, and policy frameworks.

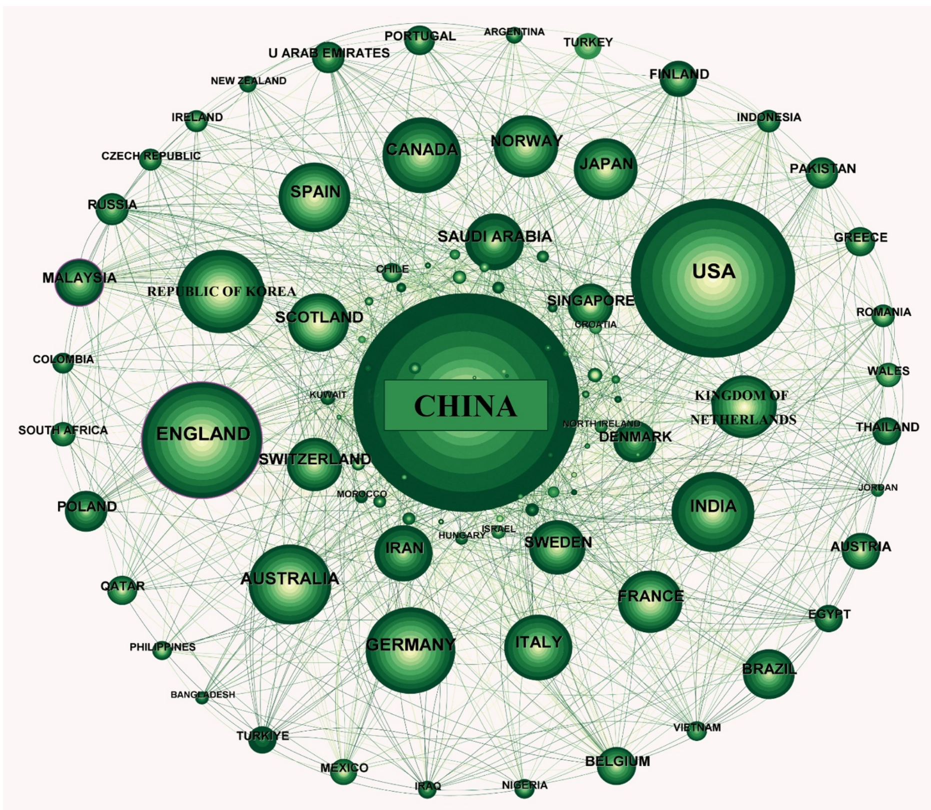

FIGURE 4 | Global research collaboration patterns in CCS-related publications. Each node represents a country, with the node size indicating the total number of CCS publications. Connections between nodes indicate coauthorship relationships; countries highlighted with purple rings have high betweenness centrality, reflecting their bridging roles within the global collaboration network.

broader applications [20]. One of the most notable examples from this phase is the SACROC project, launched by Chevron in Scurry County, Texas, in 1972 [21]. This was the world's first large-scale CO_2-EOR project, which utilized naturally occurring CO_2 transported through pipelines to boost oil recovery. By 2010, the project had injected more than 175 million tonnes of

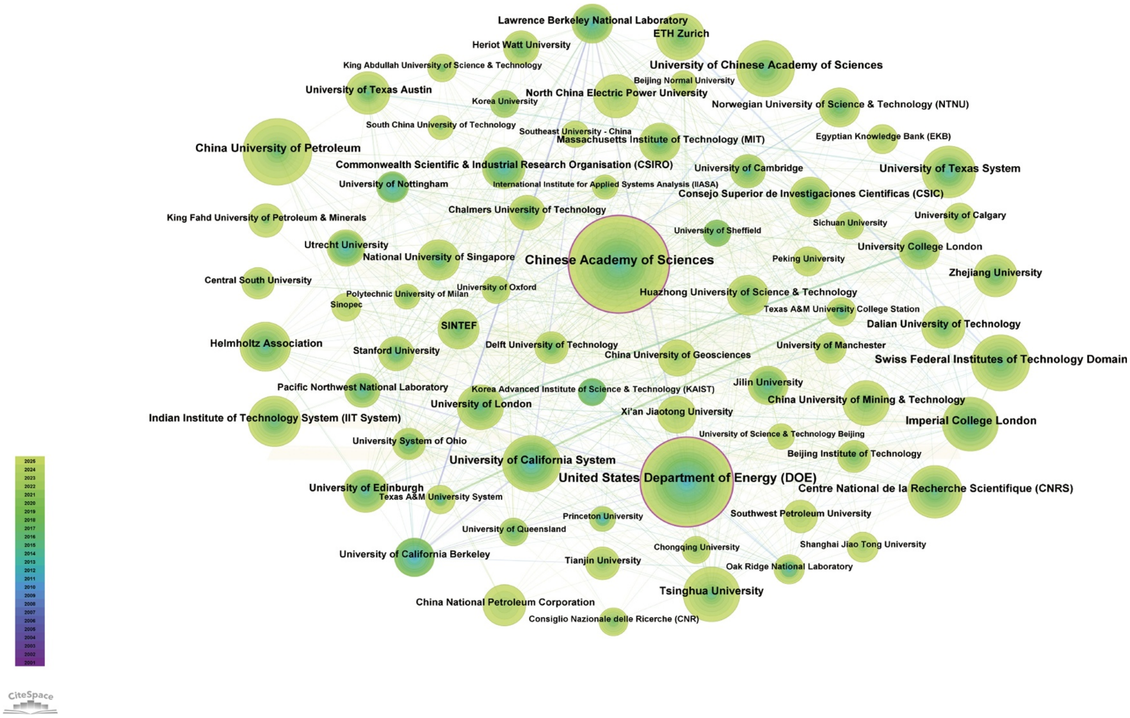

FIGURE 5 | Global institutional coauthorship network in CCS-related publications. Each node represents a research institution, where the node size indicates the total number of publications and the link thickness reflects the strength of collaborative ties between institutions. The color gradient corresponds to the average publication year, with warmer colors representing more recent contributions.

TABLE 1 | Development phases of carbon capture and storage (CCS) technology (1972–present).

Characteristics	Early exploration (1972–1995)	Demonstration and commercialization (1996–2009)	Innovation and scaling (2010–present)
Core focus	EOR applications, theoretical research	Technical and economic feasibility validation	Commercial deployment and integration
Key technology	Basic CO_2 injection and transport	Monitoring systems, offshore storage	Advanced capture methods, integrated systems
Scale	Single-site projects	Large-scale demonstration projects	Cross-border networks, multiple industries
Key projects	SACROC (175 Mt CO_2)	Sleipner (20 Mt), Weyburn–Midale (35 Mt)	Boundary Dam, Gorgon (4 $Mt \cdot a^{-1}$), Northern Lights
Primary drivers	Economic benefits from EOR	Carbon taxes, early climate policies	Net-zero commitments, climate urgency
Industry involvement	Oil and gas sector only	Gas processing, power generation	Multisector (power, cement, steel)
Policy context	Minimal climate regulation	Introduction of carbon pricing	Global climate agreements, carbon markets
Major limitations	Limited to theoretical research	High costs, technical uncertainties	Infrastructure needs, cost optimization
Key achievements	Proved CO_2 storage feasibility	First offshore CCS, monitoring technologies	First power plant CCS, cross-border networks

CO_2, demonstrating the practicality and potential of large-scale CO_2 injection. Although initially driven by economic incentives to enhance oil production, this project inadvertently set the stage for future CCS endeavors by showcasing the feasibility of long-term CO_2 storage. Key research efforts began to shift away from purely oil recovery motivations and toward a broader climate mitigation rationale. In 1977, Cesare Marchetti proposed a visionary concept of capturing CO_2 emissions from industrial processes and storing them in geological formations to mitigate climate change [22]. His proposal provided the modern framework for CCS technology, emphasizing its potential role in addressing the growing problem of anthropogenic CO_2 emissions.

Meanwhile, industrial gas-processing plants in the Val Verde area of Texas began capturing CO_2 in the early 1970s to clean natural gas streams; it was often piped into oilfields for EOR, effectively creating a practical linkage between capture and subsurface injection. These dual currents—industrial practice and conceptual innovation—formed the bedrock of CCS development.

Despite the technical promise, commercial deployment remained extremely limited throughout this period. Institutional incentives for climate-driven CCS were largely absent, as international climate policy and carbon pricing mechanisms were still nascent. EOR dominated the application landscape, meaning that CO_2 injection was primarily a by-product of oil recovery rather than an explicit strategy for emissions avoidance. The absence of dedicated capture lines, formal storage regulation, and public awareness meant that CCS for deep decarbonization was largely a theoretical possibility rather than a deployment reality. Nevertheless, this phase provided crucial operational and scientific experience—pipelining CO_2, subsurface injection, and reservoir monitoring—that would make later large-scale CCS projects technically and conceptually feasible. Entering the late 1990s, CCS began to move beyond conceptual and pilot experimentation toward industrial demonstration. The establishment of dedicated research programs and early policy discussions on climate mitigation created the conditions for a surge of scientific and engineering interest. From this point onward, the field entered a period of rapid expansion both technologically and academically, as reflected in the bibliometric patterns shown in Figure 1.

Based on the bibliometric dataset described above, Figure 1A presents the temporal trend of CCS-related publications between 2001 and 2025. The global output of CCS research has increased almost exponentially since 2001, rising from fewer than 20 papers per year in the early 2000s to more than 2000 papers in 2024. This dramatic growth reflects the accelerating academic and industrial attention to CCS after the establishment of large-scale demonstration projects and dedicated research programs in the late 1990s and early 2000s. The surge corresponds to the industrial scaling stage (1996–2009) and the subsequent integration and commercialization stage (2010–present) described in Table 1, when CCS transitioned from isolated pilot experiments to a globally coordinated technological system. The rapid expansion of publications after 2010 further signifies the diversification of CCS research, extending from capture and storage engineering to emerging topics such as CO_2 utilization, hydrogen integration, and cluster-based deployment. This trend not only mirrors technological maturation but also marks CCS's growing role within the broader net-zero and decarbonization agenda. To better understand how this surge in research activity translated into tangible technological progress, the following sections examine the subsequent stages of CCS evolution—first the demonstration and early commercialization phase (1996–2009), and then the technological innovation and scaling phase (2010–present).

Figure 1B displays the geographical distribution of CCS-related publications, revealing that research activity is highly uneven across countries. China contributes the largest share of publications (22%), followed by the United States (14%) and England (7%), whereas Germany, Republic of Korea, Australia, Canada, India, Spain, and Italy each account for between 2% and 4%. The remaining 30% of publications are distributed across a wide range of countries, indicating a long tail of smaller but widespread research participation. This pattern reflects a dual structure in the global CCS research landscape: a core group of high-output countries driving a substantial proportion of the literature and a broad peripheral group demonstrating increasing but still fragmented engagement. Although publication shares alone do not reveal specific research orientations, the figure underscores the existence of regional research hubs and highlights the expanding internationalization of CCS research beyond traditional industrial economies.

2.2 | Demonstration and Early Commercialization Phase (1996–2009)

The period between 1996 and 2009 marked a turning point for CCS technology as large-scale demonstration projects were initiated to validate its technical and economic feasibility. This phase was characterized by significant policy-driven advancements, with countries such as Norway introducing carbon taxes to incentivize CCS adoption. One of the most influential milestones during this phase was the Sleipner project in Norway. Launched in 1996 by Equinor (formerly Statoil), it became the world's first offshore CCS facility aimed at reducing greenhouse gas emissions. CO_2 captured from natural gas processing was injected into the Utsira Formation beneath the North Sea. With advanced monitoring technologies such as 4D seismic imaging and gravity measurements, Sleipner provided crucial insights into the long-term safety and efficiency of geological CO_2 storage. To date, the project has stored more than 20 million tonnes of CO_2, establishing itself as a model for offshore CCS operations [23].

Another landmark project was the Weyburn–Midale CO_2 Monitoring and Storage Project, initiated in 2000 in Canada. This project integrated CO_2 injection with enhanced oil recovery in depleted oil fields, making it a pioneer in combining economic and environmental benefits. CO_2 was sourced from the Dakota Gasification Company in the United States and transported across international borders to the Weyburn oil field in Saskatchewan. Over its lifetime, the project has stored more than 35 million tonnes of CO_2 while serving as a critical research platform for studying the long-term behavior of stored CO_2. This initiative also contributed to developing international standards for CO_2 monitoring and storage, including the Canadian CSA Z741 standard and the ISO/TC 265 framework [24, 25]. During this phase, CCS increasingly came under formal regulatory and policy frameworks rather than remaining a purely experimental technology. Although the Norwegian carbon tax was introduced earlier in 1991, it provided one of the world's first stable economic incentives for large-scale CO_2 separation and storage, and its impact became fully visible during the 1996–2009 period [26]. The tax enabled operators such as Equinor to proceed with the Sleipner project at a commercial scale, where CO_2 separation and offshore injection began in 1996. During this phase, monitoring techniques also matured significantly, as time-lapse 3D seismic surveys, gravimetry, and pressure-field modeling were systematically deployed at Sleipner to demonstrate plume containment within the Utsira aquifer [27]. The Utsira Formation's capacity was conservatively estimated at more than 600 billion tonnes of CO_2 storage potential, providing abundant subsurface storage space for decades to come.

Despite these advances, the phase also exposed key economic and institutional limitations. High upfront capital costs, lack of established CO_2 transport networks, and uncertain revenue streams beyond EOR constrained wider deployment. For example, although Sleipner demonstrated technical viability, the tariff-based business model remained heavily subsidized and dependent on Norwegian tax policy rather than standard market mechanisms. Similarly, the Weyburn–Midale project produced perhaps the most comprehensive dataset on CO_2 geological storage, but its reliance on the synergy of EOR, research funding, and cross-border cooperation highlighted the fragility of translating demonstration success into scaled replication. Moreover, public and regulatory scrutiny began to emerge: The long-term permanence of storage and the risk of leakage were raised as concerns in both academic and policy circles. As the decade closed, the demonstration phase set the stage for the next stage of CCS evolution—commercial rollout and infrastructure integration. The proof of concept achieved in this period enabled CCS to shift from pilot projects toward industrial deployment, but to move further required the development of CO_2 transport hubs, dedicated storage sites, and broad-based policy frameworks that transcended individual projects.

2.3 | Technological Innovation and Scaling Phase (2010–Present)

Since 2010, CCS technology has entered a phase of rapid innovation and scaling, supported by growing global commitments to decarbonization and achieving net-zero emissions. This period has seen the deployment of diverse CCS applications across multiple industries, including power generation, steel production, and cement manufacturing. One of the most notable projects in this phase is the Boundary Dam Carbon Capture Project in Canada. Launched in 2014 by SaskPower, it was the world's first large-scale CCS project at a coal-fired power plant [12]. The facility uses Shell's CANSOLV technology to capture up to one million tonnes of CO_2 annually, which is either stored underground or utilized for EOR. The success of Boundary Dam highlighted the viability of retrofitting existing power plants with CCS technology, offering a pathway for decarbonizing the energy sector.

Other significant projects include the Gorgon CO_2 Injection Project in Australia, which began operations in 2019 [28]. As one of the largest CCS projects globally, it aims to store up to four million tonnes of CO_2 per year from natural gas processing operations. Meanwhile, Europe has made strides with the Longship initiative, launched by Norway in 2020. This ambitious program includes the Northern Lights project, which is developing infrastructure for transporting and storing CO_2 captured from industrial sources across Europe. By creating a cross-border CO_2 network, the project aims to scale up CCS adoption across industries and countries, further demonstrating its role in meeting international climate goals. These milestones illustrate CCS's journey from theoretical concepts to large-scale implementations, showcasing its potential as a cornerstone technology for global climate mitigation efforts (Table 1). As CCS continues to evolve, its integration with emerging technologies and policy frameworks will likely drive further advancements, expanding its applicability and accessibility in the fight against climate change.

During this phase, the focus shifted decisively toward commercialization, cost reduction, and ecosystem development. The Boundary Dam project received federal and provincial support and provided a real-world test bed for post-combustion capture technologies and integration into existing fossil fuel infrastructure, including generation units, amine absorption systems, and co-utilization of captured CO_2 in EOR. The Gorgon project, although ambitious, exposed the practical limits of scaling—injection operations at the Dupuy Formation under Barrow Island faced reservoir pressure issues and captured rates well below initial targets, demonstrating that large-scale deployment still entails geotechnical risk and business model uncertainty. Simultaneously, modular capture technologies, advanced materials (e.g., high-capacity solvents and next-generation membranes), and digital monitoring tools (such as time-lapse seismic, CO_2 plume tracking, and artificial intelligence-driven reservoir modeling) emerged, accelerating the possibility of cost-effective and reliable CCS systems. Industry reports estimated that costs per ton of CO_2 captured might fall significantly, yet the rate of decline has proven slower than hoped.

Crucially, the scaling era also exposed the structural challenges of integrating CCS into broader decarbonization architectures. Although many technoeconomic barriers were addressed, the broader system issues—such as transport infrastructure, regulatory liability regimes, water management in reservoirs, and public acceptance—became more visible [29, 30]. For instance, the scheduling delays, capture shortfalls, and cost overruns at Boundary Dam and Gorgon underscored that deployment is not simply a function of individual technology maturity but of institutional, financial, and governance frameworks [31]. Moreover, the diversification of CCS into hard-to-abate industries such as steel, cement, and hydrogen production required shifting from fossil fuel-derived CO_2 to more distributed industrial CO_2 sources, thereby challenging traditional capture-storage value chains. As a result, CCS is increasingly conceived not only as an add-on technology but also as a platform for large-scale industrial transformation. As CCS enters its maturation decade, the direction of future deployment will hinge on its ability to transition from isolated large-scale projects to interconnected, multisector infrastructure networks. Integration with renewable generation, hydrogen systems, and BECCS (bioenergy with CCS) will be pivotal.

At the same time, strategic policy instruments such as long-term carbon contracts, cluster-based storage hubs, and cross-border storage frameworks will determine whether CCS becomes an enabler of systemic decarbonization or remains a niche option. What matters now is not only the deployment of individual megaprojects but also their embedding into a resilient and equitable climate infrastructure—one that spans states, industries, and continents.

2.4 | Knowledge Structure and Research Evolution in CCS Studies

The intellectual landscape of CCS research has undergone a profound transformation over the past decade. To systematically characterize this evolution, we employed CiteSpace-based keyword co-occurrence and burst detection analyses on publications from 2012 to 2025.[1] These methods reveal not only the structural organization of CCS-related knowledge but also its temporal progression from material- and process-level studies toward integrated, policy-relevant, and digitalized systems thinking.

Figure 2 depicts the keyword co-occurrence network, outlining the structural relationships among recurring research themes. The network demonstrates a dense, multicore structure centered on carbon capture, carbon dioxide storage, and CO_2 capture, which collectively represent the technological foundation of the field. Closely associated clusters—including adsorption, metal–organic frameworks (MOFs), porous materials, gas separation, and temperature—reflect the early dominance of materials science and process optimization approaches during 2012–2016. These efforts were primarily focused on improving sorbent efficiency, selectivity, and regeneration costs, establishing CCS as a viable industrial process. From 2017 onward, the research structure began to diversify markedly. Emerging nodes such as hydrogen production, energy storage, optimization, simulation, life-cycle assessment (LCA), and machine learning indicate an expanding interface between CCS and broader decarbonization technologies. The increasing co-occurrence of renewable energy, BECCS, and negative emissions suggests that CCS has progressively evolved from a stand-alone mitigation technology to a critical component of integrated carbon management and net-zero energy systems.

Figure 3 illustrates the temporal evolution of CCS research hotspots, capturing the sequential rise and attenuation of dominant themes between 2012 and 2025. Early bursts (2012–2016) concentrated on adsorption mechanisms, geological sequestration, and flue gas treatment, emphasizing physical and chemical capture routes. The mid-phase (2017–2020) witnessed the expansion of system-oriented concerns, including energy consumption, process integration, and ecosystem services, reflecting growing attention to operational efficiency and environmental co-benefits. In contrast, the most recent period (2021–2025) is characterized by intellectual convergence around negative emissions, public perception, policy frameworks, real options analysis, and storage risk assessment. This transition underscores a paradigmatic shift—from optimizing individual technologies toward evaluating societal feasibility, policy instruments, and systemic reliability under long-term decarbonization targets.

Together, these bibliometric patterns reveal a field in transition. CCS scholarship has expanded from its early focus on adsorption materials and subsurface storage to embrace the multidimensional architecture of carbon management, encompassing technoeconomic assessment, digital simulation, and governance mechanisms. This evolution signifies CCS's maturation into a cornerstone of integrated net-zero strategies, where engineering advances, system modeling, and policy design are increasingly interlinked within a unified framework for global decarbonization.

3 | Deployment Landscape and Sectoral Integration of CCS

As CCS technologies have transitioned from conceptual development to commercial maturity, understanding their deployment landscape and sectoral integration has become central to evaluating their real-world contribution to decarbonization [32]. CCS now serves as a pivotal instrument in global climate strategies, providing a means to substantially reduce carbon emissions from energy production, heavy industry, and emerging hydrogen systems [33]. With the intensification of global net-zero commitments, the number and diversity of CCS projects have expanded rapidly, encompassing a wide range of sectors and geographical contexts [34, 35]. This growth reflects both technological maturation and institutional learning, as countries move from demonstration projects to networked industrial clusters and integrated carbon management systems.

Yet, the deployment landscape remains highly uneven. Although several industrialized economies have achieved operational maturity through robust policy frameworks, financing mechanisms, and public–private partnerships, many emerging and developing economies continue to face structural barriers, including limited infrastructure, uncertain regulation, and financing constraints [36, 37]. These disparities reveal that CCS diffusion depends not only on technological readiness but also on policy coherence, institutional capacity, and cross-sector coordination [38–40]. In the following analysis, the global CCS deployment landscape is examined through the interplay of regional strategy, sectoral integration, and technological development, highlighting how CCS is evolving from a collection of isolated industrial projects into a cornerstone of comprehensive, multisectoral decarbonization systems.

3.1 | Global Research Landscape and Comparative Frameworks for CCS Deployment

To assess the global development of CCS, it is essential to first examine how actively different countries and institutions have engaged in CCS-related research and innovation. Mapping the spatial distribution of research activity provides an indirect yet powerful indication of national investment priorities and technological capacities in the field. Figure 4 presents the country-level co-occurrence network. The network clearly shows that China, the United States, and the United Kingdom dominate global CCS research in terms of publication volume and network centrality. China has become the largest contributor, reflecting both its rapidly expanding industrial CCS projects and growing governmental support for carbon management technologies. The United States maintains a strong position built upon its long-term Department of Energy-funded programs and early demonstration projects, whereas the United Kingdom leads Europe's research and offshore storage initiatives. Surrounding this core group is a second tier of advanced industrialized economies, including Germany, Japan, Australia, Canada, Norway, Kingdom of the Netherlands, and India. These countries maintain strong institutional linkages and active research programs, often specializing in specific technological niches such as offshore storage (Norway and Kindom of the Netherlands), process engineering (Germany and Japan), or industrial decarbonization (Australia and Canada). A third cluster comprises countries with growing but less consolidated CCS activities, such as France, Italy, Republic of Korea, Spain, Switzerland, and Saudi Arabia. Their involvement is supported by targeted research initiatives or pilot projects but remains more limited in scale. At the periphery of the network, several resource-rich or capacity-constrained economies—including Brazil, South Africa, Vietnam, Egypt, and Malaysia—appear as emerging participants. In these contexts, CCS is increasingly recognized in policy rhetoric and long-term climate strategies, yet its practical implementation remains at an early or aspirational stage. Figure 5 presents the institutional collaboration network, highlighting the dominant role of the Chinese Academy of Sciences (CAS), the U.S. Department of Energy (DOE), and leading European universities such as Imperial College London, ETH Zurich, and the Norwegian University of Science and Technology (NTNU). The close correspondence between the national and institutional maps suggests that countries with higher research intensity also host globally influential institutions. This alignment underscores the interaction between state-level policy priorities and institutional research capacity, forming a reinforcing cycle that accelerates CCS innovation and deployment.

Collectively, these collaboration networks indicate that CCS development is driven by a combination of national commitment and institutional leadership. The China–U.S.–UK triad dominates both academic production and demonstration project deployment, whereas secondary clusters in Europe and East Asia continue to strengthen global knowledge diffusion. Building on these patterns, the following subsection reviews how China and the United States, as the two most research-intensive and deployment-active countries, have advanced CCS through national policies, funding programs, and large-scale demonstration facilities.

Understanding why CCS deployment succeeds in some countries but falters in others requires more than listing enabling factors. It demands a structured analysis of the interlocking conditions that shape national implementation trajectories. Building on comparative energy policy literature and policy implementation theory, we develop a four-dimensional framework that captures both the upstream drivers and downstream constraints of CCS deployment in diverse national contexts [41, 42]. We begin with policy mechanisms, which function as the primary levers through which governments influence firm behavior and investment decisions. These include carbon pricing schemes, subsidies, regulatory mandates, and contractual guarantees such as contracts for difference. Although necessary, these instruments alone are not sufficient [43].

Their effectiveness depends on a country's national capacity, such as its institutional, financial, and technical ability to coordinate complex infrastructure projects, enforce regulations, and sustain long-term commitments. Countries with strong governance, stable financing channels, and effective public–private coordination are better positioned to operationalize policy instruments [44]. However, even where policy and capacity are present, the organizational structure of deployment—how projects are planned, governed, and spatially configured—determines whether economies of scale, risk-sharing, and cross-sector synergies can be achieved. We distinguish between isolated pilot projects and integrated industrial clusters, as the latter are increasingly viewed as a pathway to viable and large-scale CCS systems [45, 46]. Finally, we analyze deployment outcomes and constraints, focusing on which countries have translated policy ambition into actual infrastructure, which barriers remain, such as public opposition, legal ambiguity, and financing gaps, and which contexts exhibit persistent implementation failures [47]. Together, these four dimensions form a coherent analytical lens for comparing national CCS and Carbon Capture, Utilization and Storage (CCUS) trajectories. They allow us to move beyond policy intentions and assess the real-world interplay between design, capacity, structure, and execution. We categorize countries into three main clusters based on their institutional capacity, economic structure, and policy orientation: (A) high-capacity industrialized countries with active deployment, (B) resource-rich emerging economies with strategic motivations, and (C) capacity-constrained countries with limited implementation. This typology allows us to uncover common mechanisms and barriers within each group.

3.1.1 | High-Capacity Industrialized Countries With Active Deployment

High-capacity industrialized economies—such as the United States, China, the United Kingdom, Norway, Kindom of the Netherlands, Australia, and Canada—have taken the lead in institutionalizing CCS deployment through comprehensive policy frameworks and coordinated public–private action [48–50]. Their approaches, although contextually distinct, share common characteristics: clear long-term decarbonization targets and regulatory certainty that have enabled a stable environment for large-scale investment and innovation.

The United States and China collectively account for the majority of global CCS capacity, demonstration projects, and scientific output, positioning them as the two most influential actors in the global CCS landscape [51]. Both nations have translated technological capability and industrial scale into substantial deployment momentum. However, their institutional logics differ sharply. The U.S. model is predominantly market-driven, leveraging fiscal incentives, such as the 45Q tax credit and the Inflation Reduction Act, to stimulate private investment and innovation across decentralized state-level initiatives [52]. In contrast, China's approach is centrally coordinated under its "dual-carbon" targets, emphasizing state-led demonstration clusters and the strategic role of State-owned enterprises (SOEs) in integrating CCS into national industrial policy [53–55]. Although the United States and China collectively lead in scientific output, pilot-scale demonstrations, and pipeline development, their contributions to operational capture capacity differ sharply. The United States dominates current global capacity, whereas China remains a research-intensive and demonstration-oriented player whose large-scale projects are still under construction. Thus, China's prominence in CCS reflects its expanding industrial policy commitments and R&D intensity rather than its present share of global capture volume. Together, these contrasting yet large-scale models underscore that global leadership in CCS can emerge through distinct pathways—market liberalization and state orchestration—each shaping the pace and direction of industrial decarbonization.

In the United Kingdom, CCS development has been structured around a cluster-based model, integrating industrial emitters, transport networks, and offshore storage sites. The East Coast Cluster and HyNet North West were the first to receive Track-1 funding under the UK Industrial Decarbonization Strategy, marking a decisive policy shift from pilot projects to regional infrastructure deployment. The policy architecture combines carbon contracts for difference (CCfD) to guarantee price stability, statutory mandates under the Climate Change Act, and coordinated planning through the North Sea Transition Deal, forming one of the most sophisticated governance systems for CCS worldwide [56–58]. Norway, often cited as a global frontrunner, exemplifies a state-led and internationally coordinated approach. Its Northern Lights project, part of the Longship program, demonstrates cross-border cooperation in which CO_2 captured in Norway is transported and stored offshore under government-backed agreements with neighboring European countries. This model benefits from full government cost coverage, strong public acceptance, and rigorous monitoring protocols, setting an international benchmark for transparency and long-term reliability [59]. In the Kindom of Netherlands, the Porthos project in Rotterdam illustrates how CCS can be embedded within broader European climate governance. Supported by the EU Innovation Fund, the Dutch government has introduced a guaranteed carbon price floor and incorporated CCUS into its national climate strategy. However, public concerns about onshore storage have redirected national efforts toward offshore sequestration, underscoring the social acceptability dimension of technological integration [60]. Beyond Europe, Australia and Canada have emerged as key non-European contributors to global CCS capacity. Both host large-scale projects, such as Gorgon in Australia and Quest in Canada, typically initiated by fossil fuel companies and sustained through varying degrees of governmental financial and regulatory support [25, 28]. These projects highlight how CCS deployment in resource-rich economies often relies on leveraging existing industrial infrastructure and aligning corporate incentives with national climate objectives.

Collectively, these cases reveal that early and consistent policy commitment, regulatory clarity, and risk mitigation mechanisms are decisive in advancing CCS from demonstration to commercial scale. Although institutional design varies, the shared emphasis on cluster coordination, government–industry partnerships, and adaptive policy instruments provides a common blueprint for accelerating system-wide deployment in other industrialized and emerging economies.

3.1.2 | Resource-Rich Emerging Economies With Strategic Motivations

Although advanced industrialized economies have built formalized CCS governance structures, a different trajectory emerges in resource-rich emerging economies such as Saudi Arabia, the United Arab Emirates (UAE), India, and Indonesia. In these contexts, the strategic deployment of CCS is often shaped not only by decarbonization goals but also by industrial policy priorities, such as maintaining fossil fuel revenues, ensuring energy security, and positioning for future low-carbon export markets [61]. This dual-purpose framing introduces a distinct policy logic, wherein mitigation and fossil fuel preservation coexist within the same CCS narratives.

In Saudi Arabia and the UAE, national oil companies, such as Saudi Aramco and Abu Dhabi National Oil Company (ADNOC), respectively, have emerged as central actors in CCS deployment. These projects are primarily oriented toward EOR and increasingly framed within "blue hydrogen" strategies, aiming to align hydrocarbon exports with emerging climate standards [62–64]. For instance, captured CO_2 is injected into aging oil reservoirs to boost extraction yields while nominally reducing net emissions. Such efforts are deeply embedded within national development visions (e.g., Saudi Vision 2030 and UAE Energy Strategy 2050) and are backed by state-led investment and infrastructure planning. However, there is growing scholarly debate over whether these initiatives represent genuine mitigation pathways or merely a technocratic extension of hydrocarbon lifecycles under the guise of climate action [65]. In contrast, India and Indonesia represent lower-middle-income contexts where CCS remains at a nascent stage. Although both countries have launched pilot-scale demonstration projects and undertaken feasibility studies—such as NTPC's CO_2 capture initiative in India or collaborative programs with the Asian Development Bank and the Japan International Cooperation Agency (JICA)—their trajectories are constrained by high capital costs, policy fragmentation, and limited regulatory coherence [66, 67]. Moreover, the absence of robust carbon pricing mechanisms and uncertainty around long-term storage liabilities further dampen investor confidence. In these settings, CCS is often framed as a technical option rather than a committed pathway, contingent on external financing and multilateral cooperation.

These emerging-economy cases highlight the geopolitical diversity and strategic ambivalence embedded in global CCS deployment. Unlike the rule-based institutionalization seen in advanced economies, CCS in resource-rich emerging markets is more state-led, strategically instrumental, and often anchored in fossil fuel political economies. Understanding these dynamics is crucial for assessing both the global potential of CCS and the risks of reinforcing lock-in effects under the banner of technological mitigation.

3.1.3 | Capacity-Constrained or Low-Income Countries With Limited Implementation

A third group comprises capacity-constrained or low-income countries, including Brazil, South Africa, Vietnam, Egypt, and Kenya, where CCS is recognized in policy rhetoric but remains largely aspirational rather than operational. These nations often articulate interest in carbon capture within national climate strategies or technology roadmaps, yet practical implementation has been minimal or fragmented. The limited progress reflects not only financial and technical barriers but also broader challenges of institutional stability, policy continuity, and public legitimacy.

In Brazil, attention has centered on the potential of integrating CCS with existing hydrocarbon and bioenergy infrastructures.

Proposals for carbon storage in pre-salt oil fields and synergies with BECCS highlight the country's natural endowment and renewable potential [68]. However, actual deployment has been curtailed by political instability, restricted financing, and the absence of consistent institutional support, which together have impeded long-term project continuity and investor confidence. South Africa presents a similarly constrained case. Despite having one of the world's highest emission intensities per unit of GDP, its CCS roadmap has struggled to advance beyond the planning stage. The South African Center for CCS developed an ambitious national strategy, but pilot implementation has faced repeated delays due to funding shortages, weak technical capacity, and sustained public opposition to geological storage [69]. These issues underscore how societal acceptance and governance fragmentation can be as limiting as economic constraints. In contrast, Vietnam, Egypt, and Kenya are still in the early scoping phase, relying heavily on external donors—such as the World Bank—for feasibility studies and capacity-building efforts. In these contexts, CCS is typically treated as a long-term aspiration rather than an integrated component of national decarbonization pathways. Policy attention remains concentrated on renewable deployment and energy access, with CCUS often absent from formal implementation frameworks.

Although technological interest in CCS has diffused globally, the geography of implementation remains highly unequal. For low-income and institutionally fragile economies, advancing CCS requires not only financial assistance but also the coevolution of governance capacity, regulatory certainty, and public trust. Without these foundations, the technology risks remaining confined to policy discourse rather than becoming a viable mitigation option.

3.2 | Global CCS Project Development

As of 2024, there are 628 commercial CCS facilities in the global pipeline, representing a 60% increase from the previous year. Of these, 79 capture facilities are operational across 9 industries, with a combined operating CO_2 capture capacity of approximately 51 million tonnes per year. The facilities vary significantly in their operational status, with 50 operational facilities, 44 under construction, 247 in the Front-End Engineering and Design (FEED) stage, and 287 in early development [5]. The global operating CO_2 capture capacity is on track to double to more than 100 million tonnes per annum once facilities currently under construction commence operation. This quantitative expansion has been accompanied by a notable broadening of CCS applications across industrial sectors, reflecting its transition from a niche solution toward a core component of multisectoral decarbonization strategies. The power sector dominates, with 26 projects capturing 62.51 million tonnes of CO_2 annually [70]. Natural gas processing follows with 20 projects and a capture capacity of 42.95 million tonnes. Chemical production contributes 9 projects capturing 13.72 million tonnes annually, whereas the hydrogen sector has 16 projects capturing 13.45 million tonnes. Ethanol production, with 39 projects, captures 10.85 million tonnes annually, and the cement sector, although smaller in scale, has 3 projects capturing 3.2 million tonnes annually. Other industries, such as synthetic gas, refining, steel, and biomass energy, collectively add a capture capacity of 12.53 million tonnes per year. These numbers underline the increasing breadth of CCS applications across both fossil fuel-dependent and hard-to-abate industries [71].

Geographically, North America leads the world in CCS deployment, accounting for 63% of global capture capacity. The United States alone hosts 78 projects, capturing approximately 103.6 million tonnes of CO_2 annually, whereas Canada contributes with 8 projects. Europe follows as the second-largest region, representing 22% of global capacity, with significant projects in Norway, the United Kingdom, and Kindom of the Netherlands. The Asia-Pacific region, including China, Japan, and Australia, accounts for 9% of global capacity, reflecting growing interest and investment in CCS technology in these areas. The spatial concentration of CCS projects underscores the influence of national policy regimes, industrial capacities, and institutional readiness. To move beyond empirical mapping, we adopt a theory-informed framework to dissect the policy mechanisms and systemic barriers that determine national CCS trajectories.

3.3 | Key Technological Advancements

The global deployment of CCS projects has revealed a rapidly expanding network of facilities, countries, and institutions engaged in large-scale carbon management. Yet, the success and scalability of these initiatives ultimately depend on the maturity of the underlying technologies that enable the capture, transport, and long-term storage of CO_2. These foundations comprise three core components: carbon capture, CO_2 transportation, and geological storage [70, 72]. Over the past 2 decades, the technological foundations of CCS have progressed from early demonstrations to more mature systems capable of supporting industrial-scale decarbonization. These advancements span post-combustion, pre-combustion, and oxy–fuel capture routes, alongside improvements in CO_2 transport infrastructure and subsurface storage reliability [73, 74]. Collectively, these technological domains form the operational backbone of modern CCS and shape its prospects for large-scale integration into global decarbonization strategies.

3.3.1 | CO_2 Capture Technologies

CO_2 capture technologies have evolved along three primary pathways: post-combustion capture, pre-combustion capture, and oxy–fuel combustion. Figure 6 summarizes the three principal technological routes for CO_2 capture within the CCS framework: oxy–fuel combustion, pre-combustion capture, and post-combustion capture—each representing a distinct stage of the fuel conversion process at which carbon dioxide is separated from other gas streams.

In oxy–fuel combustion, Figure 6A shows that fuel is burned in a mixture of oxygen and recycled flue gas instead of air. The absence of nitrogen in the oxidant stream yields a flue gas composed mainly of CO_2 and water vapor, which can be readily condensed to produce a high-purity CO_2 stream suitable for compression and storage. This configuration eliminates the

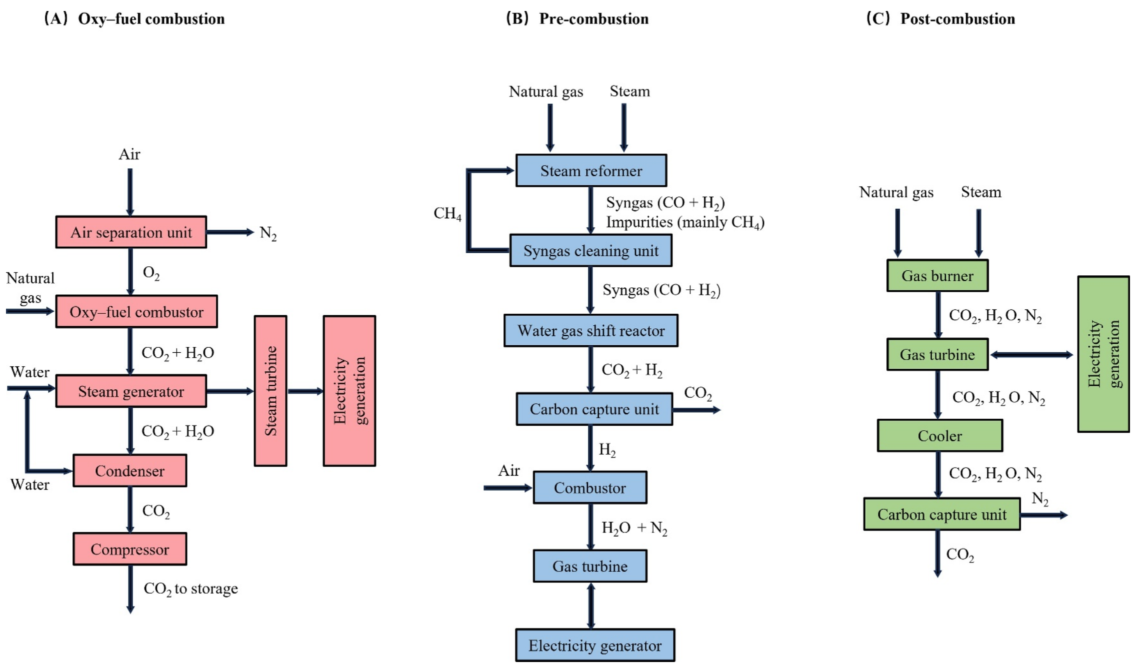

FIGURE 6 | Major technological pathways for CO_2 capture in CCS systems. (A) Oxy–fuel combustion: fuel is burned in pure oxygen, producing a CO_2- and H_2O-rich flue gas from which CO_2 is readily separated; (B) pre-combustion capture: CO_2 is removed from syngas before combustion, with hydrogen used for power generation; (C) post-combustion capture: CO_2 is separated from exhaust gases after combustion. The three pathways differ in capture stage, efficiency, and energy penalty, illustrating the trade-offs between retrofit flexibility and process integration. Reprinted from Ref. [75].

need for nitrogen–CO_2 separation but requires an air separation unit (ASU) and additional energy for oxygen production, leading to higher upfront energy costs. In pre-combustion systems, Figure 6B illustrates that carbon capture occurs prior to fuel combustion. Fossil feedstocks such as natural gas or coal are reformed with steam to produce synthesis gas (syngas, primarily CO and H_2). Through the water–gas shift reaction, CO is converted to CO_2 and H_2, after which CO_2 is separated in a carbon capture unit. The remaining hydrogen is combusted in a gas turbine to generate electricity. This approach achieves high CO_2 partial pressure, improving capture efficiency, but it requires complex gasification and reforming infrastructure, making it better suited for integrated gasification combined cycle (IGCC) plants. In Figure 6C, post-combustion capture represents the most widely applied and retrofit-compatible route. Here, CO_2 is extracted from flue gases produced after conventional fuel combustion using solvents, membranes, or solid sorbents. Because the flue gas is diluted with nitrogen, the CO_2 concentration is relatively low, leading to higher energy penalties in solvent regeneration and compression. Nonetheless, this pathway's flexibility makes it particularly attractive for retrofitting existing power plants and industrial facilities.

Overall, the three configurations illustrate the trade-offs between process integration, capture efficiency, and energy demand. Although oxy–fuel and pre-combustion systems offer higher CO_2 purity and efficiency, post-combustion capture remains dominant due to its technological maturity and adaptability to current energy infrastructure. The ongoing evolution of hybrid systems, such as chemical looping and calcium looping, aims to bridge these approaches by combining high capture efficiency with reduced energy intensity.

Among these, Figure 7 shows only post-combustion capture and pre-combustion capture have achieved full commercial maturity (technology readiness level 9). Post-combustion capture, primarily based on chemical absorption methods, is the most established and widely used technique for CO_2 capture. The process typically involves two main units—an absorber where CO_2 is captured from flue gas using a chemical solvent, and a stripper (or desorber) where the CO_2-rich solvent is regenerated through heating. A typical chemical absorption system consists of an absorption column for CO_2 capture, a stripping column for solvent regeneration, heat exchangers and pumps for process optimization, and auxiliary equipment for gas conditioning and compression. The most mature chemical absorbent is monoethanolamine (MEA), which can achieve CO_2 recovery rates of 80%–95% through a reversible chemical reaction forming carbamates [77]. Large-scale facilities such as Canada's Boundary Dam Unit 3 (BD3) and the now-retired Petra Nova project in the United States have demonstrated its effectiveness, capturing millions of tonnes of CO_2 annually. However, the process faces challenges, including high energy requirements for solvent regeneration, equipment corrosion issues, and solvent degradation over time.

The ongoing development of second-generation capture technologies aims to address these limitations. Sterically hindered amines (TRL 6–9) offer improved CO_2 loading capacity and reduced regeneration energy. The chilled ammonia process (TRL 6–7) represents another promising alternative, offering advantages such as lower energy consumption compared to conventional amine systems, reduced equipment corrosion, potential for valuable by-product formation, and better stability and resistance to degradation. These emerging technologies, combined with process optimization efforts, hold promise for

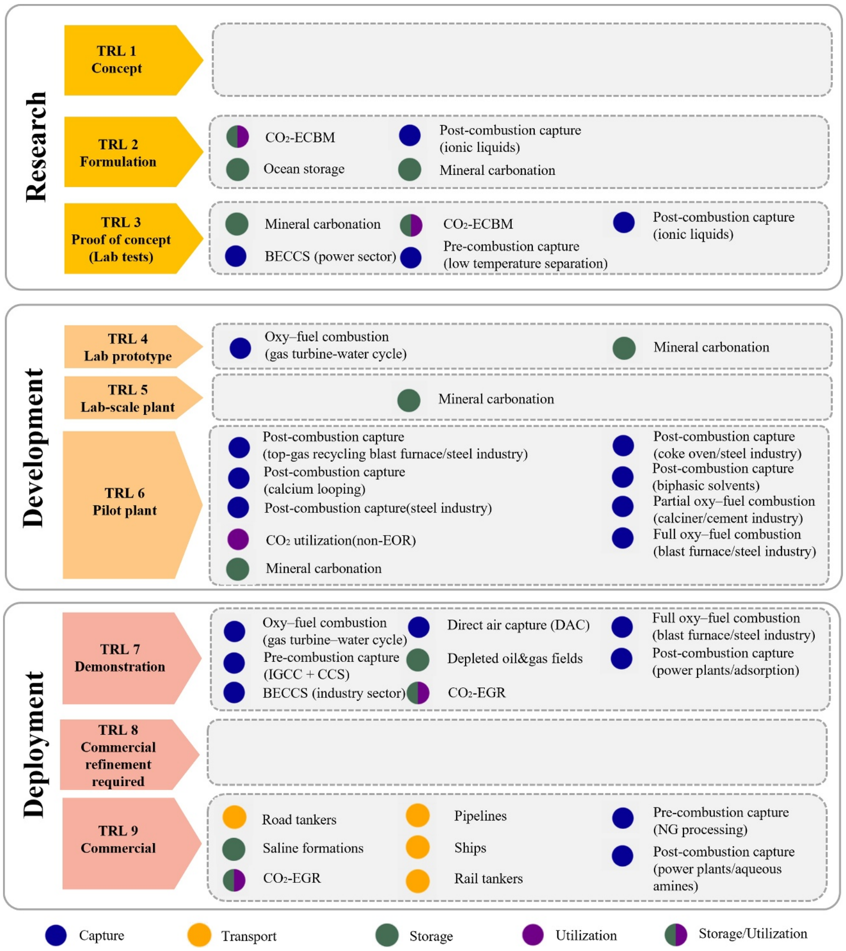

FIGURE 7 | Overall status of the most crucial element for CCS. The technology readiness level (TRL) assessment framework is divided into three main phases: research (TRL 1–3), development (TRL 4–6), and deployment (TRL 7–9). The color-coded indicators represent different aspects of carbon capture technologies, including capture (blue), transport (yellow), storage (green), utilization (purple), and storage/utilization (purple/green). Reprinted from Ref. [76].

further reducing energy consumption and operational costs in post-combustion capture systems.

Pre-combustion capture is commonly employed in natural gas processing using physical absorption methods such as Rectisol and Selexol, both of which have achieved TRL 9. This technology operates most effectively under high-pressure conditions (2–7 MPa), making it particularly suitable for integrated gasification combined cycle (IGCC) facilities [78]. In typical pre-combustion capture systems, the syngas entering the capture unit contains high concentrations of H_2 (16,390 $kmol \cdot h^{-1}$) and CO_2 (11,830 $kmol \cdot h^{-1}$) at elevated pressures of 29.58 bar and moderate temperatures of 29.44°C. Although extensively used in gas fields, its application in IGCC power plants remains in the demonstration stage, with limited large-scale implementation [75]. The higher concentration of CO_2 (15mol%–60mol%) and elevated pressure in the gas mixture significantly facilitate the separation process, resulting in lower energy expenditure compared to post-combustion capture. The separation process typically employs a 50-stage structured packing absorption column operating at these conditions, enabling efficient CO_2 removal before the H_2-rich stream is sent for power generation.

The technology can be integrated into both binary and trinary combined cycle systems, with various possible configurations for heat integration and process optimization. In binary systems, the captured CO_2 stream is compressed and cooled to 25°C and 130 bar for transport and storage, whereas the H_2-rich fuel is combusted in the gas turbine. The reformer operates at high temperatures (650°C–900°C) and moderate pressures (0.15–0.20 MPa) in the presence of a nickel-containing catalyst (up to 20wt% Ni as NiO) [79]. Trinary systems offer additional opportunities for heat recovery and efficiency improvements through more sophisticated integration schemes, achieving net efficiencies of up to 41.62% compared to 40.26% in binary systems.

Although extensively used in gas fields, its application in IGCC power plants remains in the demonstration stage, with limited large-scale implementation. The higher concentration of CO_2 (15mol%–60mol%) and elevated pressure in the gas mixture significantly facilitate the separation process, resulting in lower energy expenditure compared to post-combustion capture. Steam methane reforming (SMR) shows better performance with specific direct emissions of 1 kg CO_2 equivalent per kg H_2 compared to 1.27 kg CO_2 equivalent per kg H_2 for autothermal reforming (ATR) while maintaining similar efficiency levels (85% vs. 87%)

[80]. The integration of pre-combustion capture systems requires careful consideration of heat integration opportunities to maximize overall system efficiency while maintaining stable operation across different load conditions, which is evidenced by the various heat exchange networks shown in the system configurations.

Figure 8A [81] demonstrates combustion regions at different oxygen concentrations and preheating temperatures. Oxy–fuel combustion is at an earlier stage of development, with a technology readiness level ranging from 4 to 7. This combustion technology, which involves burning fuel in high-purity oxygen (typically > 95%) and recycled flue gas, can significantly reduce nitrogen oxide emissions and facilitate carbon dioxide capture, as illustrated in the oxy–fuel combustion process schematic [82, 83]. From a combustion chemistry perspective, this technology fundamentally alters the thermodynamic characteristics of traditional combustion processes and significantly impacts reaction kinetics.

Flame characteristics of methane/oxygen/carbon dioxide mixtures are shown in Figure 8B,C [81]. In traditional air combustion, nitrogen comprises approximately 79% of the combustion air volume, not only diluting oxygen but also significantly influencing the combustion process. In contrast, oxy–fuel combustion directly uses high-purity oxygen and controls temperature through flue gas recirculation, a fundamental transformation that brings multiple technological advantages. Research indicates that under oxy–fuel combustion conditions, flame propagation speed, ignition delay times, and critical chemical reaction pathways undergo significant changes [73, 84–86]. For instance, as the dilution of carbon dioxide and water vapor increases, flame propagation speed demonstrates an almost linear decline, arising not only from changes in physical thermodynamic properties but also from complex chemical reaction kinetics.

Despite the promising prospects of oxy–fuel combustion, numerous challenges remain, including high pure oxygen production costs, specialized high-temperature material requirements, and complex combustion dynamics [87]. Traditional low-temperature cryogenic air separation technologies, characterized by high energy consumption and substantial investment, significantly constrain oxy–fuel technology's widespread application. Consequently, researchers are actively developing more advanced air separation technologies, such as ion transport membranes and chemical looping systems, aimed at reducing energy consumption and improving separation efficiency. Simultaneously, system design and performance optimization of oxy-fuel combustion have become research focal points. By introducing innovative thermodynamic cycles such as the Allam cycle and the supercritical carbon dioxide Brayton cycle [87], researchers are continuously exploring possibilities to improve overall system thermal efficiency. These advanced

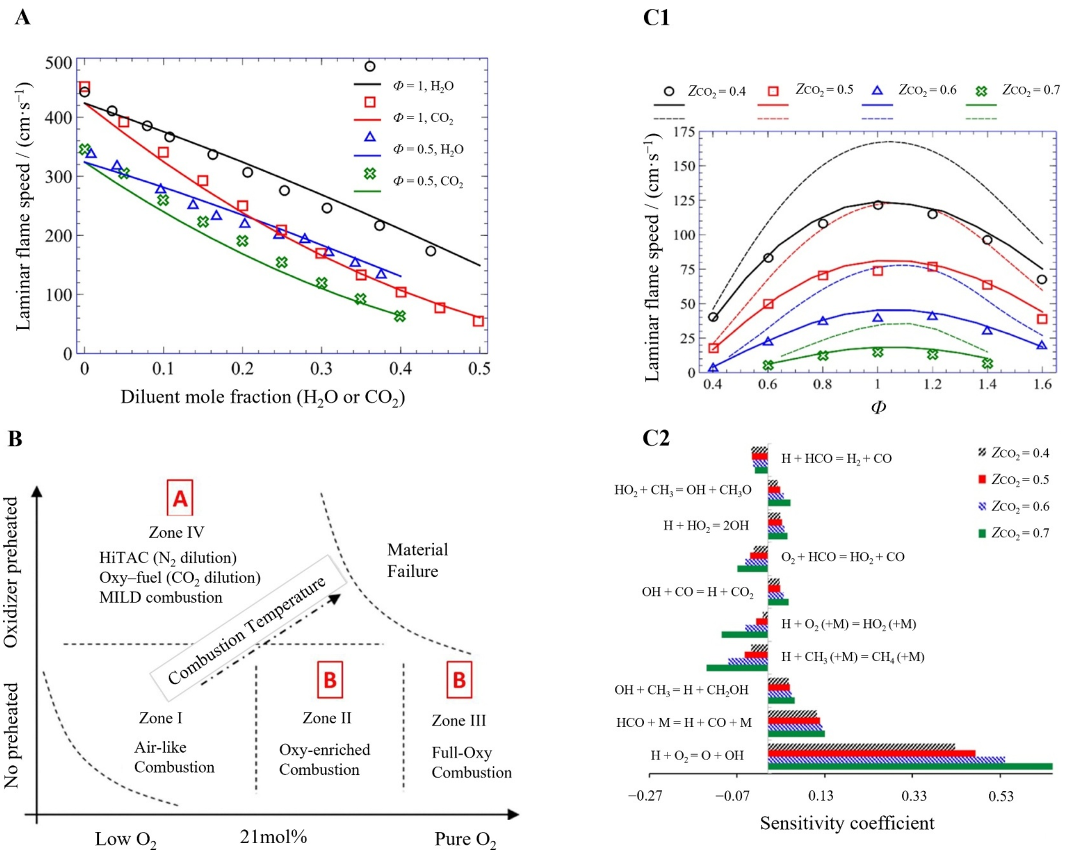

FIGURE 8 | Combustion characteristics of oxy–fuel systems. (A) Laminar flame speed of $CH_4/O_2/H_2O$ and $CH_4/O_2/CO_2$ mixtures at different dilution levels. (B) Combustion regimes map based on oxygen concentration and preheating temperature. Sensitivity analysis of (C1) methane concentrations and (C2) laminar flame speed. Z_{CO_2} denotes the CO_2 molar fraction in the oxidizer mixture; Φ represents the global equivalence ratio of the fuel–oxidizer mixture. Reprinted from Ref. [81].

thermodynamic cycles not only can recover more waste heat but also can significantly reduce system energy consumption, clearing obstacles for oxy–fuel technology's commercial application [88]. Currently, Japan leads globally in oxy–fuel technology innovation, accumulating valuable experience through multiple pilot-scale demonstration projects [89]. From power generation to industrial processes, oxy–fuel combustion technology is demonstrating immense potential in achieving near-zero emissions and driving energy transformation. As the technology continues to mature and costs progressively decrease, this innovative combustion technology promises to provide a critical solution for global climate change mitigation.

The technological evolution of oxy–fuel combustion reflects a broader trend in energy research: the pursuit of more efficient, environmentally friendly combustion technologies that can simultaneously address energy needs and environmental challenges. By reimagining fundamental combustion principles, scientists and engineers are paving the way for a more sustainable energy future, where carbon capture and efficiency are not competing goals but integrated components of advanced energy systems.

3.3.2 | CO_2 Transportation and CO_2 Geological Storage Technologies

Transporting CO_2 from capture sites to storage locations is typically achieved through pipelines or shipping. Pipelines dominate the sector, with a global network exceeding 8000 km, primarily concentrated in North America. CO_2 is typically transported in a supercritical state (at pressures of 10–20 MPa) to avoid phase changes and ensure efficient flow. Figure 9A [90] from corrosion protection studies reveals the complex environmental conditions within these supercritical CO_2 transport pipelines, highlighting the technical challenges of maintaining pipeline integrity during transport [91].

In Figure 9B [92], shipping, though less common, is gaining traction for long-distance transport [93]. Currently used for industrial and food-grade CO_2, ship-based transport typically operates at pressures of 15–20 bar and temperatures around −30° C. Recent studies suggest that 7–15 bar shipping could offer significant cost advantages, particularly for offshore storage projects. With the rise of offshore CO_2 storage projects and increasing global efforts to reduce carbon emissions, both pipeline and

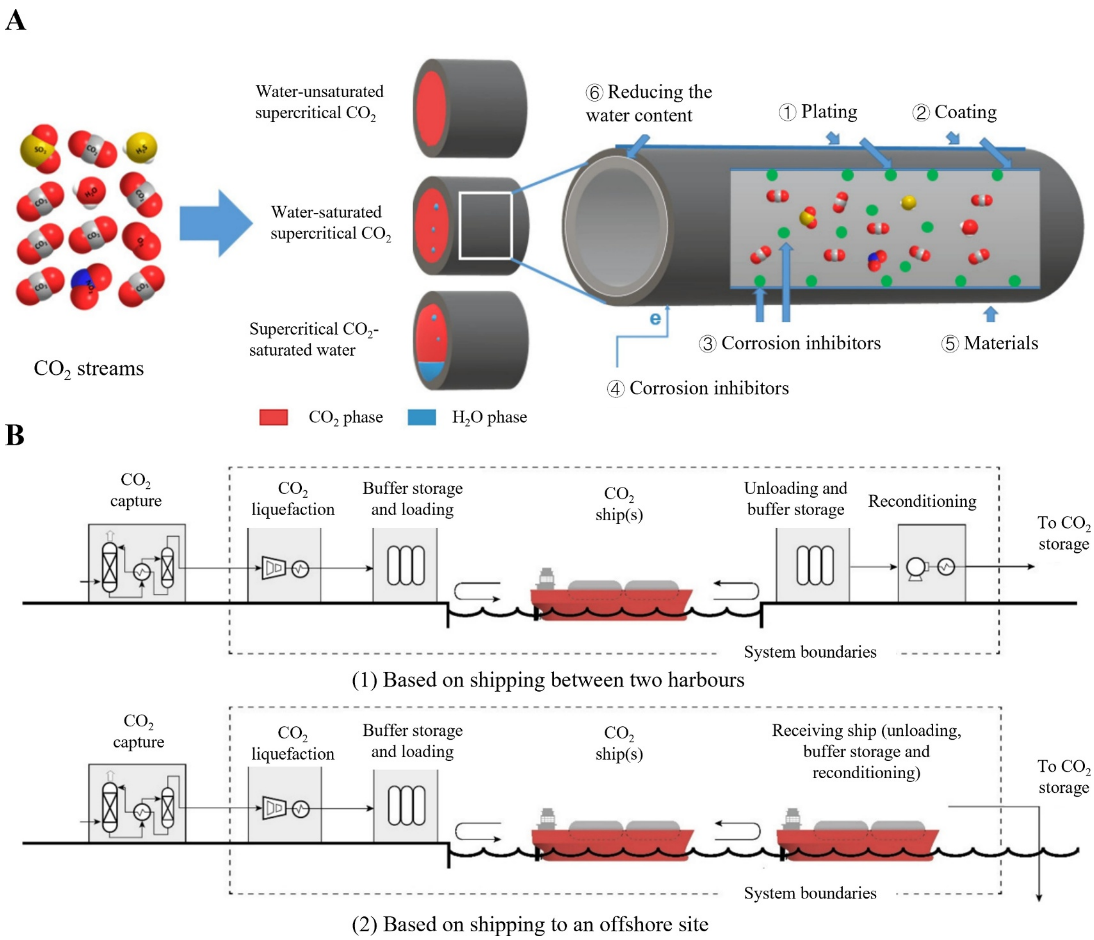

FIGURE 9 | The phase states of supercritical CO_2 under different water content conditions, including water-unsaturated and water-saturated states. (A) Highlighting important corrosion protection measures such as coatings, material selection, and the use of corrosion inhibitors. Reprinted from Ref. [90]. (B) Depicts two different CO_2 transportation scenarios: (1) transport between two harbors and (2) transport to an offshore storage site. The key steps involved in these scenarios include CO_2 liquefaction, buffer storage and loading, shipping, and final reconditioning. Reprinted from Ref. [92].

shipping transport are expected to play crucial roles in the future of carbon capture and storage infrastructure [8, 94, 95]. The choice between pipeline and shipping will depend on factors such as distance, volume, infrastructure availability, and economic considerations [96]. Geological storage remains the cornerstone of CCS, with more than 90% of projects utilizing depleted oil and gas reservoirs and deep saline aquifers for CO_2 injection. These storage methods leverage complex trapping mechanisms that ensure long-term containment of CO_2.

As illustrated in detailed geological studies, Figure 10A [97] shows that CO_2 storage involves multiple trapping mechanisms that evolve over different time scales [34, 98–100]. Initially, structural trapping prevents CO_2 from migrating upward, with buoyant CO_2 accumulating beneath impermeable cap rocks. Over time, additional trapping mechanisms come into play: Residual trapping immobilizes CO_2 droplets within pore spaces, whereas solubility trapping occurs as CO_2 dissolves into formation waters, creating denser fluid that sinks within the reservoir [101, 102].

Internationally, rigorous monitoring, reporting, and verification (MRV) systems have been developed to ensure the safety and reliability of storage sites. Techniques such as seismic monitoring, gravity surveys, and environmental sampling are routinely employed to track CO_2 migration and detect potential leakage risks. In Figure 10B [103], the comparison of trapping mechanisms in different geological formations demonstrates how various formations, such as deep saline aquifers, depleted oil and gas fields, and unmineable coal seams, provide distinct combinations of physical and geochemical trapping, enabling secure long-term CO_2 storage under varying pressure-temperature conditions.

Pioneering projects such as Sleipner in Norway have provided compelling evidence that CO_2 can be securely stored for decades without significant leakage [104]. By the end of long-term storage, a substantial portion of the injected CO_2 may be permanently trapped through mineral carbonation, where CO_2 chemically reacts with host rock minerals to form stable carbonate minerals. Although depleted oil and gas reservoirs currently dominate CCS storage strategies, emerging technologies such as basalt formations show promising long-term storage potential, offering alternative geological storage solutions for mitigating greenhouse gas emissions.

4 | Challenges and Pathways Toward System-Wide Integration

CCS technology represents a critical solution in the global effort to combat climate change through greenhouse gas emissions reduction. Although significant technological advances have

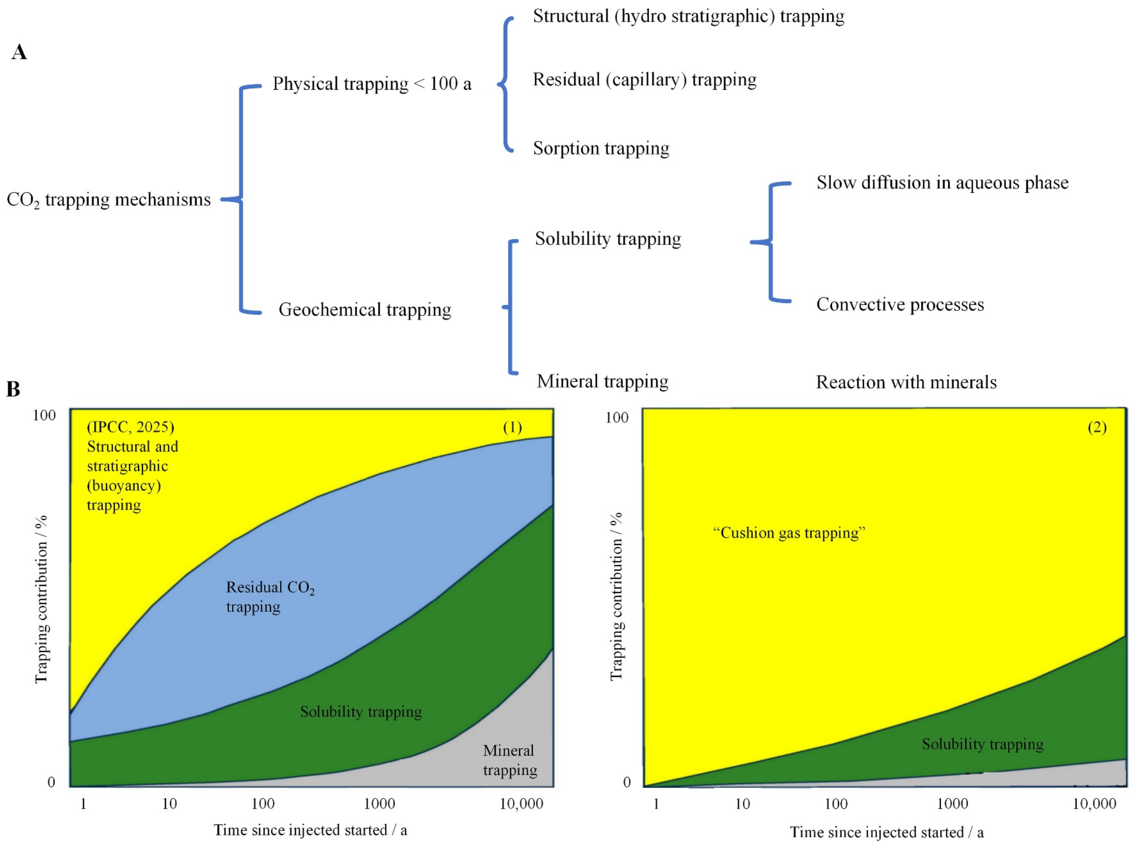

FIGURE 10 | Schematic illustration of the different CO_2 trapping mechanisms in geological formations. (A) These include physical trapping mechanisms such as structural/stratigraphic trapping and residual (capillary) trapping, as well as geochemical trapping mechanisms such as solubility trapping and mineral trapping. The timescales over which these trapping processes occur are also indicated. Reprinted from Ref. [97]. (B) Comparison of the relative contributions of these trapping mechanisms over time in saline aquifers (1) and depleted gas fields (2). In saline aquifers (1), structural/stratigraphic trapping dominates initially, transitioning to residual and solubility trapping over longer timescales. In depleted gas fields (2), CO_2 is expected to form a "cushion" below the remaining methane rather than a buoyant plume. Reprinted from Ref. [103].

been achieved, the widespread implementation of CCS faces multifaceted challenges across technical, economic, and regulatory domains. An examination of current developments and future trajectories in CCS technology underscores the critical need for accelerated innovation, enhanced scalability, and strengthened international collaboration to achieve global carbon neutrality objectives.

A first set of challenges lies in the technological domain, particularly in improving the efficiency, cost-effectiveness, and scalability of capture and storage systems. Current research priorities include the advancement of novel solvents and adsorbents with minimized regeneration energy requirements, coupled with comprehensive process optimization for enhanced energy efficiency. Innovative separation methodologies, particularly membrane-based and cryogenic separation techniques, show promising potential for transforming CO_2 capture processes. Additionally, geological sequestration remains fundamental to successful CCS deployment, with safety considerations paramount. Significant advances in geological characterization techniques and predictive modeling capabilities are essential for enhancing the precision of CO_2 migration forecasts. The implementation of sophisticated monitoring systems and early-warning mechanisms can substantially improve storage security, complemented by comprehensive risk assessment and management protocols. As monitoring technologies advance and operational experience accumulates, confidence in the long-term integrity of geological storage continues to strengthen [61, 105]. These technical hurdles, although significant, are only one part of the system-wide transition challenge.

Beyond technical performance, the large-scale deployment of CCS hinges on coordinated infrastructure and standardized operational models. The scaling of CCS operations is crucial for its effective integration into global emission reduction strategies. Saline aquifers, with their extensive storage capacity, are emerging as the predominant focus for future sequestration initiatives. The establishment of regional CCS clusters presents an optimal approach for maximizing operational efficiencies through the integration of diverse emission sources and storage locations. This expansion necessitates substantial investment in CO_2 transport infrastructure and the implementation of standardized, modular capture systems to optimize cost efficiency [106].

Realizing such deployment pathways also requires enabling policy intervention and viable market mechanisms. The development and enhancement of carbon pricing instruments provide crucial economic incentives for CCS projects. Government intervention through targeted measures, including tax incentives and subsidies, is vital for reducing adoption barriers across industries. Policy innovations, encompassing liability protection mechanisms and streamlined regulatory frameworks, are fundamental in building stakeholder confidence [107]. The establishment of comprehensive standards governing construction, monitoring, accounting, and trading practices is instrumental in facilitating broader industry adoption.

These challenges point to the limitations of isolated deployments. To realize CCS's full potential, a transition toward systemic integration is essential. In the near term, efforts focus on advancing capture technologies, pilot deployment, and regulatory development. As regional CCS clusters emerge and operational maturity improves, medium-term progress will hinge on scaling infrastructure and standardizing processes. Looking ahead to 2050, CCS is expected to function as a foundational component of industrial decarbonization, embedded in national climate strategies and supported by robust ecosystems of policy, technology, and investment. To enable this shift, emerging business models, including CO_2-EOR integration, carbon credit systems, and third-party service provision, offer promising pathways to reduce adoption barriers and enhance commercial viability. Strategic collaboration across government, industry, and academia will be essential to de-risk implementation and accelerate innovation [40].

Although national-level integration is critical, global coordination across markets, institutions, and energy systems will ultimately determine CCS's transformative impact [41]. International cooperation plays a pivotal role in diffusing knowledge and aligning incentives, particularly through cross-border research initiatives and capacity building in emerging economies. Technological breakthroughs in materials science, separation efficiency, and intelligent monitoring expand the frontier of CCS application. Synergistic deployment with hydrogen production, renewable energy, and process optimization can amplify emissions reductions through systemic coupling [108]. Realizing this potential requires coordinated planning across technical, economic, and environmental domains. Ultimately, the role of CCS in net-zero transitions will be defined not by isolated deployments, but by its ability to integrate across sectors and scales as a central pillar of decarbonization.

5 | Conclusion

CCS has evolved from a collection of engineering techniques into a system-wide decarbonization infrastructure embedded within industrial clusters, transport storage networks, and national climate strategies. Through integrating bibliometric mapping, technological synthesis, and comparative policy analysis, this review provides a unified perspective on how CCS is shaped by the coevolution of technology, institutions, and deployment architectures. Evidence from our bibliometric and CiteSpace analyses further reveals a clear intellectual transition: Global CCS research has shifted from early material and capture-mechanism studies toward themes of system integration, cluster governance, and cross-sector coordination, forming the knowledge foundation for the system-oriented perspective adopted in this review.

Across countries, our analysis uncovers a persistent mismatch between technological maturity and institutional alignment. Although capture and storage technologies have advanced substantially, deployment remains geographically concentrated and institutionally fragmented. High-capacity economies such as the United Kingdom, Norway, and Kindom of the Netherlands show coordinated cluster-based deployment enabled by policy certainty and public–private governance. Resource-rich emerging economies often employ CCS to extend hydrocarbon value chains under "blue hydrogen" narratives, with uncertain climate additionality, whereas capacity-constrained low-income countries remain structurally excluded from meaningful deployment. The bibliometric domain patterns reinforce this divergence: Countries with active CCS deployment lead research on system integration and governance themes, whereas countries with limited deployment remain concentrated in niche technical subfields.

Looking forward, this review argues that CCS must be governed not as a set of isolated technical fixes but as a system integration challenge. Three axes are fundamental: shared CO_2 transport and storage infrastructure, durable and transparent policy mechanisms, and social legitimacy built through procedural justice and robust monitoring. Failures along any of these dimensions risk locking CCS into high-cost and low-impact trajectories. Achieving strategic coherence across climate, industrial, and innovation policy domains will determine whether CCS becomes a transition enabler or a stranded asset within national decarbonization pathways.

By mapping the technological, institutional, and knowledge-domain evolution of CCS, this review contributes a multidimensional understanding of where, how, and why CCS succeeds or fails across contexts. Future research should deepen inquiry into distributional justice, post-deployment accountability, cross-border storage governance, and the enabling conditions for Global South participation. As climate commitments intensify, the key question is no longer whether CCS is technically feasible, but whether it can be embedded within credible, equitable, and strategically integrated net-zero transitions.

Author Contributions

Nan Liu: writing – original draft, software, methodology, data curation, conceptualization. **Di Liu:** writing – review and editing, methodology, data curation. **Yuqing Zhan:** writing – review and editing, methodology. **Qinqin Chen:** writing – review and editing, methodology. **Yuanting Qiao:** writing – review and editing, validation, supervision, conceptualization. **Rui Tan:** writing – review and editing, validation, supervision, conceptualization.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

[1] To ensure computational efficiency and visualization clarity, the bibliometric analysis of keyword co-occurrence and temporal evolution was conducted for the period 2012–2025, which captures the most active and data-rich phase of CCS research. Earlier records (2001–2011) were excluded due to low publication volume and sparse keyword connectivity, which may otherwise distort network density and clustering accuracy.

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