

Driving Green Port Development with Carbon Capture and Storage Applications and Prospects

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Abstract. As global warming intensifies and extreme weather events occur more frequently, reducing greenhouse gas emissions has become a shared challenge for the international community. Against the urgent global backdrop of climate change mitigation, Carbon Capture and Storage (CCS) technology has emerged as a critical component of port decarbonization strategies. This paper comprehensively analyzes its multi-dimensional benefits—environmental, economic, and social—while critically examining the challenges related to high costs, potential environmental risks, and public acceptance barriers. In response, targeted optimization strategies encompassing technological advancement and policy coordination are proposed. The effective implementation of these strategies is essential for unlocking the full potential of CCS in the maritime sector. The study concludes that CCS technology holds significant potential for enabling deep decarbonization in ports, notwithstanding existing hurdles. To inform decision-making by port authorities and stakeholders, future research should pursue techno-economic assessments and explore the integration of CCS with smart port systems.

Keywords: Carbon capture and storage; green port; techno-economic assessment.

1. Introduction

Currently, global warming driven by greenhouse gas emissions continues to escalate, while the climate crisis becomes increasingly severe. Among various sectors, greenhouse gas (GHG) emissions from international shipping and maritime transportation contribute significantly to those issues. According to the data, GHG emissions from maritime transport have ranked sixth globally. Between 2012 and 2018, carbon dioxide (CO₂) emissions from international shipping increased from 962 million tons to 1.056 billion tons without efficient reduction measures. It is estimated that by 2050, this figure will reach a maximum of 1.5 billion tons [1]. Ports, as an important part of maritime transportation and a key hub for international shipping, hold the lifeline of maritime economy and trade. Hence, their energy conservation, emission reduction and low-carbon development require immediate action. The ultimate objective is to curb the average increase in global temperature within the threshold of 2°C, accomplish the goals specified in the Paris Agreement on Climate Change, and drive the progress of global sustainable development in a steady manner [2].

Carbon capture and storage (CCS) technology can be regarded as an advanced technology that can significantly reduce greenhouse gas emissions, mitigate global climate change, and help achieve zero-carbon goals [3]. Thus it has received widespread attention from many countries, including the United States, Australia, and Canada. It has the potential to significantly reduce CO₂ emissions from different industrial sources, with applications directly relevant to the national strategies of the aforementioned countries [2]. However, CCS technology is plagued by a host of issues, including prohibitively high costs, susceptibility to causing environmental hazards, and a lack of supporting policies. These challenges have collectively contribute to insufficient research and application of CCS technology in green port construction, leaving its development still in an immature stage. Consequently, this study, which focuses on bridging this gap, possesses distinct innovative value and practical guiding significance for advancing green port development.

Based on relevant literature and data, this article will introduce the core connotations and systems of CCS technology, explain its inherent logic in green port construction. It will also systematically

demonstrate potential advantages, opportunities, risks, and challenges of CCS technology in enabling green port construction. By providing corresponding optimization methods and constructive suggestions, this paper can better assist relevant enterprises and government departments in exploring the feasibility of this technology in empowering green port construction.

2. Carbon Capture and Storage Technology and Evaluation System

2.1. Carbon Capture and Storage Technology

CCS refers to a technological process that enables the separation of CO₂ from emission sources, followed by its transportation, and ultimately its permanent storage in deep geological formations or utilization in value-added processes [4]. In 1960, the predecessor of this technology, CO₂-enhanced oil recovery (EOR), came into being. After continuous improvement and upgrading, Marchetti firstly expounded CCS's contemporary meaning, and the Intergovernmental Panel on Climate Change (IPCC) conducted the first comprehensive assessment and definition of the technology in 2005 [5].

CCS technology follows a sequential three-step workflow as Figure 1 demonstrates, with carbon capture as its initial phase. This phase primarily entails the separation, collection, purification, and compression of CO₂ generated from emission sources, and it encompasses three primary technical approaches: pre-combustion capture, oxy-fuel combustion capture, and post-combustion capture. The second step is carbon transportation, which refers to two primary modes of conveying captured CO₂, either direct transportation via pipelines, or transportation to designated storage sites by trucks or ships. The last step is carbon sequestration, which specifically refers to the process of storing the transported CO₂ in suitable deep geological formations [6].

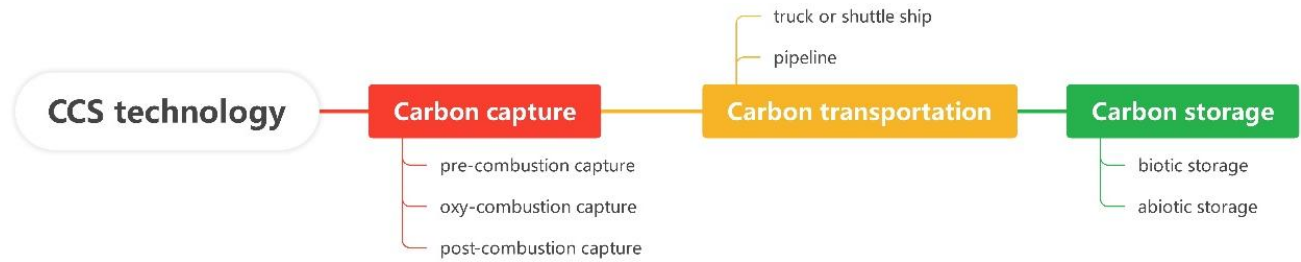


Figure 1. Process of CCS technology [6]

CCS is widely regarded as a crucial and non-negotiable technology that can effectively address climate crisis caused by excessive emissions of greenhouse gases, especially CO₂. According to IPCC, it is classified among the three obligatory carbon abatement technologies within the four core carbon mitigation technology routes [5]. CCS technology thus boasts broad application prospects in facilitating the development of green ports and driving their sustainable growth, while holding substantial value and significance for assisting ports and even the international shipping sector in attaining zero-carbon objectives.

2.2. Green Port Evaluation and Targets

According to the Organization for Economic Co-operation and Development (OECD), green port evaluation can be divided into three aspects: maritime emissions, port activities, and inland transportation [7]. These three aspects share a key common metric, which is the emission of greenhouse gases, notably CO₂. As an integrated transportation hub incorporating ships, heavy-duty machinery, vehicles, and other industrial equipment, ports exhibit high CO₂ emissions. Taking Shanghai Port as a case in point, its annual carbon dioxide emissions reached 141,805.40 tons [7]. Against this backdrop, countries have implemented a series of measures including penalties and the shift to clean energy to curb CO₂ emissions from ports. Therefore, the fundamental objective of green ports is to regulate GHG especially CO₂ emissions so as to mitigate the occurrence of extreme weather events triggered by climate change and further align with the temperature control targets established under the Paris Agreement.

2.3. Rationale for Carbon Capture and Storage in Green Ports

The construction of green ports takes the control of greenhouse gas as its core focus. In accordance with OECD standards, all three of its evaluation dimensions consider carbon emissions as the key indicator. From the berthing of ships to the operation of heavy machinery in port areas and hinterland freight transportation, carbon emissions are significant across all links of port operations. Currently, measures such as financial penalties and the transition to clean energy can curb emissions to a certain extent; however, in the face of the complex equipment systems and dynamic operational scenarios of ports, they still have limitations in achieving in-depth emission reduction.

CCS technology can precisely solve these problems, and its "carbon capture, transportation, sequestration" process is highly adaptable to port scenarios. The capture step separates CO₂ from the exhaust gases of ships and machinery through three methods. The transportation step leverages the existing port network for transfer via pipelines, trucks or ships. The sequestration step can adopt marine sequestration technology in a location-specific manner to enhance efficiency and convenience. As one of the four core carbon emission reduction technologies recognized by the IPCC, CCS technology narrows the gaps of existing measures and overcomes the challenges in equipment replacement simultaneously, thus making great contributions to the construction of green ports and providing a new approach for the sustainable development of global maritime industry.

3. The Advantages of Carbon Capture and Storage

3.1. Environmental Benefits

As an advanced technology for decarbonization, CCS enables the capture and utilization of CO₂ directly at its emission sources, thereby demonstrating significant environmental benefits.

Decarbonization strategies encompass a dual framework of supply-side and demand-side measures [8]. On the demand side, CCS technology capture CO₂ from flue gases and exhaust emissions produced by vehicles, cargo handling equipment, ships, and other industrial facilities. This capture process directly contributes to a substantial reduction in GHG emissions arising from port machinery operations, vehicle transportation, industrial manufacturing activities, and ship operations themselves. On the supply side, CCS technology enables the conversion of captured CO₂ into reusable energy sources like natural gas, alongside its application in various other sectors. In 2022, nearly two-thirds of CO₂ capture facilities were dedicated to natural gas processing, which is a practical implementation scenario distinguished by minimal operational expenses with an annual capture capacity of 28 million metric tons of CO₂. In addition, it also includes hydrogen production, electricity, heat and other industries [9]. The U.S. Gulf Coast serves as a prominent example of energy transition. The application of CCS technology in this region has achieved remarkable success, delivering benefits that span multiple states and national interests while earning certification from the Oil and Gas Climate Initiative (OGCI). The region's coastal industries—including natural gas export, heavy oil refining, and hydrogen production—are highly aligned with the supporting industrial facilities near ports, making this area a highly representative case for studying port energy transition [10]. Furthermore, integrating CCS technology with existing offshore wind and photovoltaic power could form a more robust and sustainable energy system, thereby accelerating related technological development and industrial upgrading.

Furthermore, the photosynthetic activity of extensive marine flora enables effective carbon sequestration [6]. Data indicates that the ocean can absorb nearly 30% of human-induced carbon emissions [11]. Together, these factors establish the ocean as a highly efficient natural carbon sink. Due to the unique locational advantages of coastal ports, the application of ocean storage can significantly improve the efficiency and convenience of storing carbon dioxide generated in ports. Overall, CCS technology delivers substantial environmental value to the development of green ports, serving as both a core enabler and critical underpinning for advancing the green and low-carbon transition of port operations.

3.2. Economic Benefits

CCS technology also delivers significant economic benefits for green port construction, particularly within carbon economy. Carbon economy refers to various trading initiatives and relevant financial policies implemented to reduce GHG emissions. Currently, the global carbon market is expanding. The formulation and evolution of carbon markets have carried profound significance for addressing capital bottlenecks in low-carbon economic advancement, optimizing the carbon emission trading mechanism, and elevating the core competency of a nation's economy [12]. Besides, a growing number of countries have embarked on the implementation of carbon taxes, and as of 2020, thirty nations and regions had put this policy into practice [13]. It is worth mentioning that 11 national or lower level governments have imposed a carbon tax rate of at least \$25 per ton [13]. Consequently, excessive GHG emissions clearly place ports and the shipping industry at a competitive disadvantage in the global carbon trading market.

Accordingly, the storage and reuse functions of CCS technology can reduce or even avoid unnecessary costs such as fines and carbon tariffs caused by excessive carbon emissions in ports. Simultaneously, it allows ports to obtain a favorable position in the global carbon market, generating additional advantages and achieving multiple objectives at once. And as illustrated in Figure 2, CCS technologies are set to take on a critical function in energy shift, enabling the reduction of carbon emissions from both operational and newly built fossil fuel-powered electricity facilities, as well as the manufacturing of blue hydrogen sourced from fossil fuels with low carbon intensity [8]. The natural gas and hydrogen regenerated through this process can be sold or recycled by port supporting facilities and related industries, thus generating additional profits. With the iteration and large-scale application of CCS technology, the equipment cost and energy consumption of its operation in ports are expected to gradually decrease, further enhancing the cost advantage and economic sustainability of ports in green transformation.

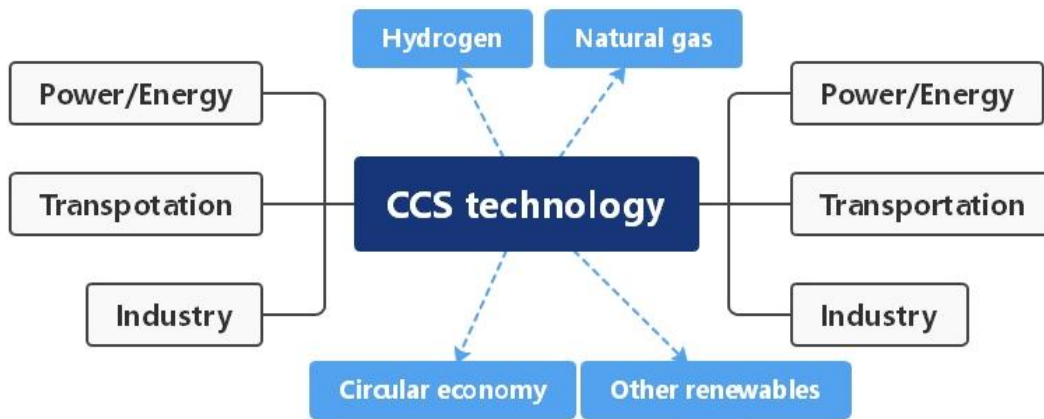


Figure 2. The role of CCS technology in energy transition and recycling [8]

3.3. Social Benefits

According to the Global CCS Institute, the CCS-PI index evaluates the policy support and guarantees for CCS technology across countries based on nine factors. Elevated scores signify more advanced policy frameworks. As of 2018, Norway, the United Kingdom, the United States, China, Canada and Japan ranked relatively high in CCS-PI scores, which indicates that these countries boast the most robust policy landscapes and application safeguards for CCS technologies. By 2020, 28 large-scale CCS initiatives had been operational across the globe, boasting an aggregate storage volume of 41 million metric tons per annum. Additionally, 38 further projects were in the planning and construction phase, with a storage volume of 76.41 million metric tons per annum [8]. All these data demonstrate that CCS technology is advancing in a positive direction. The public's understanding of CCS is gradually becoming more comprehensive with an increasing recognition of this technology.

By deploying CCS technology, ports can foster international exchange and cooperation on relevant technologies, demonstrate their commitment to green development to the public, enhance public recognition of their eco-friendliness, and mitigate the “Not In My Backyard” (NIMBY) effect caused by carbon emissions. Meanwhile, as a benchmark for the application of low-carbon technologies, port can foster a demonstration effect, drive upstream and downstream enterprises in the shipping industry chain to participate in emission reduction, create a large number of jobs, and promote the transformation of the regional green economy. The United Kingdom serves as a case in point, its government had pledged a minimum expenditure of £800 million to facilitate the progression of CCS technology, which created 3,850 job positions in the initial year [14]. An improved employment landscape can further bolster public confidence in CCS technology. Ultimately, amid international port rivalry, ports with proficiency in CCS technology are able to strengthen their attractiveness through green labeling, obtain a greater number of low-carbon trade contracts, and boost their core competitiveness and brand equity in the global maritime transportation network.

4. Challenges and Optimization Strategies

While bringing the above benefits and opportunities, the application of CCS technology also faces many difficulties and challenges, which has led to certain obstacles in the technology's role in enabling green port construction. Based on these issues, there are corresponding solutions and optimization measures.

4.1. Economic Cost Challenges and Response Strategies

In terms of the economic dimension, CCS is confronted with substantial cost pressures. It entails high initial costs, stemming from the requirement to establish relevant infrastructure and implement advanced core technologies. In addition, a series of additional costs will be incurred due to the energy needs of the capture phase, the continuous operation of equipment, and the regular monitoring procedures [15]. Data indicates that the capture phase alone accounts for 60–80% of the total cost of CCS, with the cost of capturing each ton of carbon dioxide typically exceeding \$50 [4]. This high cost is largely attributed to the need for large-volume solvent replenishments [5]. For the coal-fired, natural gas-fired, and other power generation facilities that may be deployed as supporting infrastructure at ports, the initial investment required for those integrated with CCS technology is approximately twice that of their counterparts without CCS implementation [4]. Concurrently, CO₂ is frequently treated and managed as a form of waste material, thus leading to public misunderstanding and doubts about the application value of CCS technology [15]. Consequently, high costs remain a primary deterrent for port-related companies and industries considering CCS adoption.

To address this, a multi-faceted approach to cost reduction is essential. The cost of CCS is influenced by multiple factors, including technological maturity, CO₂ concentration at emission sources, industrial processes, project layout, and carbon pricing [4]. These factors, in turn, provide actionable insights and strategies for reducing the costs associated with CCS technology. Firstly, it is feasible to advance technological innovation and large-scale deployment, conduct targeted planning based on current demand for CCS technology, develop low-cost capture solvents while optimizing transportation routes, and address gaps as well as concentrate efforts on tackling key challenges in the underdeveloped technologies and projects related to CCS at present. Secondly, a diversified cost-sharing mechanism can be established: governments may lower the threshold for initial investment through special subsidies and low-interest loans, while introducing relevant policy incentives. Meanwhile, small and medium-sized ports should be supported in jointly establishing regional CCS alliances to share equipment and transportation costs, thereby optimizing the benefit distribution structure of CCS technology application in ports. Thirdly, efforts should be made to explore the feasibility of integrating CCS technology into carbon markets, remove relevant barriers hindering investment and financing channels, and strengthen guidance for investment institutions [4].

4.2. Environmental Challenges and Response Strategies

In terms of the environmental dimension, risks run through the entire CCS chain. From the perspective of carbon capture, extra emissions of capture plants will exacerbate air pollution in the port area. Additionally, some kinds of chemical solvents employed in the capture process pose a potential risk of contaminating water quality, subsequently endangering human health. Meanwhile, the increased energy demand in this link will also generate other pollution [14]. From the standpoint of carbon sequestration, the marine carbon sequestration approach most likely to be adopted by ports carries the potential to induce ocean acidification, which in turn exerts adverse impacts on the marine ecological environment [6]. Furthermore, the development of marine carbon sequestration remains in a nascent stage, large-scale deployment of this technology will still require a considerable period of time to materialize. From the perspective of geological storage, its risks mainly come from three aspects. Firstly, there may be a leaking transmission channel that connects with atmosphere, water layer and geological storage bodies. Secondly, adverse geological phenomena such as earthquakes and faults may be triggered by the injected CO₂, which might in turn cause pipeline leakage. Thirdly, under the action of external forces, CO₂ stored in the strata may leak, further causing local pollution [5]. It is evident from the above that these three aspects share a commonality, all of them can trigger the leakage of sequestered CO₂, thus posing significant hazards to vegetation, human personnel, and the ecological environment.

In response to the above issues, relevant preventive and corrective measures can be taken in each process. First and foremost, a full-chain monitoring system should be established, with targeted measures implemented across each stage, low-volatility solvents and additional waste gas treatment devices shall be adopted in the capture phase; real-time leakage monitoring sensors and emergency shutdown systems shall be deployed during the transportation stage; pre-construction geological stability assessments shall be conducted for sequestration sites, alongside the establishment of long-term monitoring networks; and hierarchical emergency response plans shall be formulated. Secondly, in terms of cross-border cooperation, national and international laws can be leveraged to regulate the cross-border movement of CO₂, as well as its disposal and monitoring in underground reservoirs, thus ensuring that all countries share achievements, while providing mutual support and coordination [8]. Finally, various departments and enterprises within ports should also establish mechanisms for CCS-related responsibility allocation and risk prevention and control, ensuring the realization of benefit-sharing and risk-bearing among all parties [4].

4.3. Policy Barriers and Public Acceptance Deficiency

In a substantial number of countries, societal acceptance of CCS technology remains relatively low, and this phenomenon applies even to major economies including Australia, Germany and China [8]. According to a survey, CCS technology is controversial in the Netherlands and the public lacks sufficient confidence in the technology. At its root, the lack of such acceptance stems from societal indifference and perfunctory attitudes toward climate action, which makes it difficult to formulate policies regarding this technology, thus hindering its development. Furthermore, the general public's insufficient understanding and knowledge of CCS technology constitute another key factor impeding the full-scale CCS implementation. Another argument posits that carbon tax policies enthusiastically pursued by certain countries impose substantial additional costs on specific industries—costs typically passed on to consumers. This, in turn, fosters public resistance toward CCS, a technology deployed to comply with the mandatory carbon emission reduction policies enforced by these nations [15]. In essence, the promotion of CCS technology depends not only on favorable government policies but also, crucially, on public awareness, understanding, acceptance, and active endorsement.

To address this situation, the top priority is to enhance public engagement with CCS technology. This can be achieved by leveraging the role of highly educated experts, scholars, and government officials in advocacy and outreach, while highlighting CCS technology's potential economic benefits and vast potential for creating employment opportunities [8]. Secondly, industries and governments should advance information disclosure and promote public participation, which can enhance the general

public's trust in the technology. In conclusion, a relational chain can be formed among various links. The general public first develops sufficient understanding of and confidence in CCS technology. Subsequently, governments and relevant authorities provide robust support for the technology, leading to stronger governmental support and the formulation of supportive policies and measures, particularly encouraging its application within the port industry [15]. This pathway will ultimately facilitate the full-scale implementation of CCS technology.

5. Conclusion and Outlook

5.1. Conclusion

CCS technology, which captures CO₂ from emission sources for transport and permanent storage, offers multifaceted advantages spanning environmental, economic, and social dimensions. However, it also confronts an array of challenges, including generally prohibitive costs, significant disparities in port locations and scales, and the immaturity of core technical components.

Notwithstanding these challenges, CCS technology retains broad application prospects in green port development. If further optimized and refined based on the current technological foundation, the technology will better serve green port initiatives and leverage its unique advantage of significantly reducing CO₂ emissions. Looking ahead, the widespread adoption of CCS across various ports worldwide will drive the low-carbon transition of international shipping, enhance operational efficiency, and foster the vigorous growth of maritime trade. Ultimately, this progression will contribute substantially to the advancement of global sustainable development.

5.2. Outlook

This study systematically elaborates on the application advantages, core challenges, and optimization strategies of CCS technology in green port construction, providing an important technical pathway and decision-making reference for deep decarbonization in the port sector. However, this review has certain limitations. Firstly, it focuses on qualitative analysis and lacks quantitative modeling and comparative analysis of the cost-benefit of applying CCS technology in ports of different scales and regions. Secondly, the discussion primarily centers on the technology itself, with insufficient exploration of the specific pathways for deep integration of CCS with existing port management systems and digital platforms.

Future research could further deepen the work by conducting case studies and techno-economic assessments for specific ports to quantify the initial investment, operational costs, and long-term environmental benefits of CCS projects, thereby providing more precise data support for investment decisions.

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