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Post-Combustion CO_2 Capture: Barriers and Pathways for CCS Deployment

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Abstract. Through the systematic analysis and study of existing literature, this paper examines the main difficulties faced by carbon capture and sequestration (CCS) in the wider application of post-combustion chemical absorption. Through the findings of the review, studies have shown that the high cost of CO_2 capture of $60-150 per ton of CO_2 and the low price of carbon of $5-10 per ton of CO_2 together constitute major economic obstacles to large-scale use. In addition, this challenge is closely related to many problems repeatedly reported in the literature, including high energy consumption, limited economies of scale effects, solvent degradation, corrosion after long equipment time, and insufficient policy support. Existing research generally believes that these obstacles are interrelated, and it is difficult to really solve a single problem to achieve a wide range of commercial applications. Overall, the literature shows that further progress will depend on the coordinated advancement of technological innovation, carbon pricing mechanisms and policy support, among which an effective carbon pricing system is widely regarded as one of the key factors in facilitating the large-scale deployment of CCS.

Keywords: CCS, chemical absorption, deployment barriers

1. Introduction

1.1. Research background

Climate change is one of the most serious challenges facing mankind today. Since the industrial revolution, the concentration of Carbon Dioxide (CO_2) in the atmosphere has increased from 280 ppm to more than 400 ppm, and the global temperature has continued to rise [1]. There are three main paths to achieve CO_2 emission reduction: energy transformation, energy efficiency improvement, and carbon capture and removal. Carbon Capture and Storage (CCS) represents an important option for reducing process-related emissions from industries such as cement and steel, where direct electrification or renewable energy alone is insufficient. Previous studies have estimates that CCS can contribute 13% of the global cumulative emission reduction [2, 3].

As the world's largest carbon emitter, China is committed to reaching a carbon peak by 2030 and carbon neutrality by 2060.It has been estimated that China will still need to capture or remove approximately 1.4 billion tons of CO_2 through CCUS by 2060 [4-8].

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However, large-scale deployment of CCS has yet to be achieved. Although the post-combustion chemical absorption method has verified the technical feasibility in projects such as Boundary Dam and Petra Nova, and the IPCC has also confirmed its emission reduction potential [1], only 17 large CCS projects in the world are in operation worldwide [2, 9]. The gap between technical feasibility and large-scale deployment raises an important question: what factors restrict the wider deployment of CCS? Given the limited time available to achieve carbon neutrality targets, understanding these barriers has become increasingly important. This question constitutes the starting point of this article's review.

1.2. Research problems

Existing CCS research has made substantial progress in three main areas: the improvement of technical efficiency, the estimation of capture costs, and the case analysis of individual projects. These studies provide a good basis for understanding the technical feasibility of CCS. However, recent studies have pointed out, existing studies tend to focus on single-dimensional risks (technical barriers account for 27.1% and security risks account for 26.6%), while there is relatively little attention to how multi-dimensional risks affect each other and jointly restrict the promotion [6]. Therefore, the systematic analysis of multi-facetted barriers to popularization in the existing literature is still relatively limited.

Specifically, most studies tend to discuss technology, economy, policy and other factors separately, and pay less attention to the interrelationship between them.

Based on this, this article focusses on a core issue: how can the four dimensions of cost, technology, policy and society influence each other and jointly restrict the promotion of post-combustion chemical absorption CCS? Answering this question will help reveal the deep and specific reasons behind CCS's "technically feasible, slow in popularization".

1.3. Research objectives

This research aims to: (1) summaries the technical principle and application status of chemical absorption method; (2) systematically analyses the main barriers to CCS deployment; (3) explore possible solutions on the basis of analyzing the mutual influence of various obstacles.

1.4. Significance of research

At the theoretical level, this review places more emphasis on the interaction between the obstacles than by considering them alone. Such changes provide a different perspective for understanding CCS deployment. Most of the existing studies discuss technology, economy, policy and other factors respectively. This article provides a more comprehensive analytical perspective to study how these factors affect each other and jointly limit the popularization of CCS.

At the practical level, the research conclusions can provide reference for policymakers and industry parties to help figure out which obstacles are the most critical and how to deal with multiple obstacles at the same time through policy tools, so as to avoid over-reliance on a single solution.

1.5. The structure of the thesis

This article first introduces the research background and core research issues. Then, it introduces the technical basis of CCS, including the principle of chemical absorption and its current application. After that, this article reviews the deployment obstacles reported in the literature, studies the

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interrelationship between these obstacles, and discusses potential solutions. The last part summarises the key findings and limitations of the research.

2. CCS technical foundation

2.1. Technical principle

Among the available CCS technologies, post-combustion chemical absorption is the most commercially mature capture technology. Compared with pre-combustion capture and oxy-fuel combustion, it can be retrofitted to existing industrial facilities without major modifications to the production process, making it more suitable for large-scale deployment.

In this process, the amine solution absorbs CO_2 in the flue gas in the absorption tower at 40-60°C, and the rich liquid is heated in the regeneration tower at 110-130°C to release CO_2, and then sealed or utilised after compression [1]. The capture rate can reach 80-90%, and the renewable energy consumption is approximately 2.0-4.0 GJ/t CO_2 [2].

Despite the maturity of technology, the method still has limitations such as amine degradation, equipment corrosion, high energy consumption, etc., which restricts its economy [2, 5].

2.2. Application status

There are many large-scale CCS projects around the world. For example, the Canadian Boundary Dam, built in 2014, captures 1 million tons of carbon dioxide every year. In 2017, Petra Nova in the United States captures 1.6 million tons of carbon dioxide per year. Other representative facilities include the Australian Gorgon built in 2019 with an annual injection capacity of 4 million tons and the Canadian Quest built in 2015, with an annual catch of 1 million tons [2, 9].

As of 2023, there are 17 large-scale CCS projects in operation around the world. Although progress has been made, the figure is still far below the level required to achieve the climate mitigation target.

Most of the projects are located in North America and Europe, indicating that the deployment of CCS is gradually expanding rather than experiencing rapid large-scale growth. In China, Guohua Jinjie Power Plant captures 150,000 tons of carbon dioxide every year, which is China's largest coal-fired power plant CCS demonstration project, but the difference is that its construction relies on government subsidies [4].

3. Obstacles to the promotion of CCS: documentary evidence

3.1. Barriers to CCS promotion reported in the literature

Given the limited number of CCS projects currently in operation, it is necessary to examine the barriers that restrict its large-scale deployment. Comprehensive literature can identify four types of obstacles.

Cost barrier.It has been reported that the capture cost is about 60-150 USD/ton of CO_2, and the capture link accounts for 60-70%, while the average price of the global carbon market is only 5-10 USD/ton, with a gap of more than ten times [3]. It has also been noted that the efficiency of power plants decreased by 8-12 percentage points after installing CCS [2]. Existing studies consistently identify cost as the primary barrier, and the gap between capture costs and carbon prices is widely regarded as the main economic constraint, although cost estimates vary depending on project scale and analytical assumptions.

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Technical obstacles. Previous studies have pointed out that the degradation of amine solution during operation needs to be supplemented regularly, and the acidic environment causes equipment corrosion [2, 5]. These technical problems are widely recognised in the literature, but there are different views on the time limit for solving - some studies are optimistic about recent technological improvements, whereas others argue that these challenges are likely to persist under commercial operating conditions.

Policy obstacles. It has been observed that most countries have carbon prices that are too low and policy signals that remain unclear [3]. Policy support has been identified as crucial for projects to enter the implementation stage [9]. Most studies consider policy intervention essential for promoting CCS deployment, but there are differences on which tool is most effective—some studies tend to favour carbon pricing, while others emphasize subsidies or tax credits.

Social obstacles. Research has found that the closer the CCS facility is to the residential area, the higher the public opposition [10]. Similar findings have been reported in a number of subsequent studies.

Overall, the literature consistently identifies cost as the primary barrier, while technological, policy, and social factors further reinforce its effects. However, the relative importance of these barriers varies across regions and individual studies.

3.2. Documentary evidence on the relationship between obstacles

The four types of obstacles described above do not function independently. Combing the literature can be found that there is a causal relationship and a mutually reinforcing relationship between various obstacles.

First, low-carbon prices directly lead to high costs that cannot be recovered. Studies have clearly pointed out this causal chain: if there is not enough carbon pricing, enterprises cannot recover the collection cost regardless of technical efficiency [3]. This shows that there is a direct relationship between the carbon pricing policy and the economic feasibility of the CCS project.

Second, high cost and small number of projects reinforce each other and form a cycle. Some studies have pointed out that the small number of projects cannot equalise the unit cost through the effect of scale, and the high cost hinders the new project [2]. This forms a negative feedback cycle: the fewer projects, the higher the unit cost; the higher the unit cost, which further inhibits the development of the project.

Third, policy uncertainty magnifies the obstacles in both technology and economy. When the policy signal is unclear, enterprises are reluctant to invest in research and development and large-scale facility construction [9], thus slowing down the cost decline brought about by technological progress. Therefore, unstable policy support has further strengthened the barriers in both technology and economy.

Fourth, social opposition interacts with policies and economic factors. Public opposition will increase project delays and costs, which will worsen economic feasibility and inhibit investment [10]. On the contrary, a clear policy framework and community participation help alleviate opposition - indicating that there is a mutually constrained relationship between policy factors and social factors.

In a word, the literature shows that these four obstacles are not simply superimposed, but multiplying each other: without considering the interaction between the obstacles, it is difficult to achieve substantial improvement as a whole by solving one obstacle alone.

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3.3. Synthesis of findings

Combining the above literature, the core constraint of CCS promotion is the gap between the capture cost and the carbon price. The capture cost is about 60-150 USD/ton of CO_2, while the average price of the global carbon market is only 5-10 USD/ton, which is more than ten times the gap [3]. This means that enterprises will face significant economic losses when installing CCS without external incentives.

This gap is continuously reinforced by three interrelated obstacles. First, high energy consumption and lack of scale effects make CCS fall into a vicious circle, because high costs inhibit investment, and small projects cannot reduce costs through scale effects. Second, it is a technical problem. Amine degradation and equipment corrosion continue to push up operating costs. Third, it is the failure of the policy. The low price of Ling carbon and the unclear signal make it impossible for enterprises to form stable investment expectations. The three obstacles reinforce each other, making it difficult for CCS to achieve scale through a single-point breakthrough [2, 3, 10].

4. Discussion

4.1. Summary of the main findings

Based on the above analysis, CCS deployment is constrained by four interrelated barriers: cost, technology, policy, and social acceptance. The literature consistently suggests that the gap between capture costs and carbon prices remains the primary obstacle to large-scale deployment. More importantly, these barriers do not operate independently but reinforce one another, creating a self-reinforcing system in which progress in one area alone is unlikely to achieve substantial overall improvement. The literature therefore suggests that overcoming these barriers requires coordinated efforts across technological development, policy support, economic incentives, and public engagement.

4.2. Comparison with existing studies

This finding is consistent with previous research that pointed out that existing studies focus on single risks but ignore their interrelationship [6]. It is also consistent with the findings that the economic efficiency of China's CCS subsidies is lower than that of the renewable energy policy portfolio [7]. This shows that policy design must take into account the interaction between obstacles.

There are different views on the role of CCS in the carbon neutralization path in the literature. Most studies believe that CCS is an indispensable emission reduction technology. IPCC (2005) has listed CCS as a key emission reduction option [1]. It has also been pointed out that most comprehensive evaluation models cannot achieve the 2°C target without CCS [2]. Some research consider CCS an essential component of carbon neutrality [3].

However, some studies have reservations. It has been found that the economic efficiency of CCS subsidies in China's power industry is lower than the combination of "renewable energy subsidies + carbon pricing" [7], suggesting that the economic competitiveness of CCS needs to be evaluated more carefully. Some views believe that CCS may slow down the transformation of energy structure and unreasonably extend the use period of fossil energy. This kind of discussion is relatively rare in the existing literature.

These differences may reflect variations in research scope and analytical context. Studies adopting global assessment models tend to emphasize the necessity of CCS, as few alternatives are

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currently available for achieving deep decarbonization. By contrast, studies focusing on specific national contexts, particularly those where the cost of renewable energy has declined rapidly, tend to take a more cautious view of the cost-effectiveness of CCS. In addition, studies using different modelling approaches, such as techno-economic analysis, often reach different conclusions because they adopt different assumptions regarding technological learning rates and policy conditions. These differences suggest that the deployment of CCS is not only a technical or economic issue, but is also closely related to broader choices regarding energy transition pathways.

4.3. Research implications

Based on the above analysis, three revelations can be drawn, all of which are based on the literature summarized.

First, the single-dimensional solution has limited effect. It has been showed that the efficiency of subsidies alone is lower than that of the policy combination [7], indicating that interventions that only target a single obstacle are difficult to work when other obstacles are not resolved. This means that policy design should go beyond a single tool idea.

Second, carbon pricing may be a key lever. Many studies have shown that raising carbon prices can directly narrow the gap between costs and carbon prices and increase investment incentives [2, 3]. However, this inference needs more empirical verification - what level of carbon price can trigger investment and whether it varies from industry to industry. At present, the literature is not clear.

Third, the policy tools of each country are different - the United States focusses on tax credits, Europe focusses on carbon trading, and China focusses on government demonstration projects, but a single tool has not completely solved the problem of promotion. This suggests that instrument choice and combination should be tailored to each country's institutional context and economic conditions, a point also emphasised in cross-country comparisons [3].

4.4. Research limitations

This article has several limitations.

First, most of the cost data discussed in the reviewed studies are based on design-stage estimations rather than long-term operational data. Therefore, the actual costs during practical application may differ from the reported values. In addition, variations in estimation methods, system boundaries, and assumed operating conditions among different studies may affect the comparability of cost results.

Second, the literature reviewed in this article mainly includes English and Chinese publications from 2020 to 2025. Studies published before 2020 or in other languages were not considered, which may result in the omission of some relevant research findings, particularly the operational experiences and lessons learned from earlier CCS demonstration projects.

Third, this article mainly provides a qualitative analysis of the existing literature. It does not quantitatively evaluate the relative significance of different barriers, nor does it establish a quantitative model to analyze the interactions and causal relationships among these influencing factors.

Fourth, due to the limited number of available studies, this article primarily focuses on post-combustion chemical absorption technology, while other CCS pathways are discussed to a lesser extent. Therefore, the applicability of the conclusions drawn in this review to other CCS technologies requires further investigation.

4.5. Suggestions for future research

Based on the above limitations, the following four future research directions are proposed.

(1) the actual cost and operational data of the CCS project in operation should be collected to verify the existing estimate. At present, most of the cost data comes from forecasts in the design stage, and the gap between these forecasts and actual performance is not clear.

(2) the interaction between various obstacles should be quantitatively analysed. Although this article has described these interactions qualitatively, the relative strength and key leverage points of each causal relationship still need to be empirically tested.

(3) the cost-effectiveness of different policy combinations should be compared, such as the different combinations of subsidies, carbon taxes and carbon transactions. The existing literature provides limited information in the context of different countries.

(4) the factors affecting public acceptance and their relationship with policy design should be further studied. Public opposition has led to the delay or obstruction of multiple CCS projects, but there is still little research on how the policy framework can mitigate such opposition.

5. Conclusion

This article focusses on the post-combustion chemical absorption CCS technology, and systematically expounds the basic principle of the technology, the progress of practical application, and various practical obstacles faced by the current large-scale implementation.

Based on the existing research, it can be seen that the chemical absorption method is one of the most mature CCS technical routes at this stage. However, judging from the actual implementation, the speed of the promotion of this technology is still difficult to match the pace of the carbon neutrality target. In the past two decades, only 17 large-scale CCS projects have been put into operation globally. The core problem that restricts the large-scale development of projects is reflected in the long-term misalignment between the cost of carbon capture and the market carbon price.

This imbalance between costs and benefits mainly stems from three types of interrelated practical problems: high system energy consumption, insufficient industrial scale, some key technical problems have not been fully overcome, and there are still shortcomings in the supporting policy system. Multiple problems are intertwined to form a systematic development bottleneck. Relying on single technology optimization or partial improvement alone, it is difficult to effectively promote the large-scale application of CCS technology.

At present, there are still different views on the application value of CCS technology in the academic community. Some studies point out that CCS is a key supporting technology to ensure the global achievement of the 2℃-temperature control target. Some studies also question the economic benefits it generates, while worrying that this technology may delay the replacement process of renewable energy systems. It can be seen that the study and judgement of the development of CCS technology needs to be combined with the overall strategy of energy transformation of various countries.

Different from the existing research on single sorting problems, on the basis of summarizing the obstacles to the development of CCS, this article further analyses the intrinsic relationship and superimposed influence of various constraints, and constructs a set of comprehensive analysis frameworks to explain the development status of the technology that is "technically feasible and economically limited". Framework analysis shows that the development dilemma of CCS technology is not caused by a single factor, but by the systematic limitations formed by the coupling

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of various constraints. This comprehensive constraint mechanism has been less systematically discussed in previous studies. At the same time, this article is qualitative review research. It has not carried out a quantitative analysis of the impact weight of various obstacles, and the best policy plan to adapt to the development of CCS has not been selected. It can be further supplemented and improved through empirical research in the future.

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