

The Research of the Reasons Why the Post-Combustion Carbon Capture with Amine-Based Processes is Expensive and Studies on Low-Cost Improvement Technologies

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Abstract. Carbon capture and storage (CCS) is widely regarded as a critical technology for achieving deep decarbonization and global net-zero emissions. However, despite its significant potential, large-scale deployment of CCS remains limited, primarily due to high economic costs that hinder commercialization. This paper provides a comprehensive review of the technological and economic challenges associated with post-combustion amine-based carbon capture, which is currently the most mature and widely applied capture approach. A systematic analysis of the cost distribution across the CCS value chain reveals that the capture stage contributes approximately 60–80% of the total lifecycle cost, mainly due to high capital and operational expenditures. The substantial energy demand for solvent regeneration is identified as a major factor contributing to the high cost of amine-based systems. The paper further compares various cost-reduction strategies, including process optimization, advanced solvent development (such as mixed amines, phase-change solvents, and ionic liquids), and emerging technologies including solid adsorption and membrane separation. The analysis indicates that conventional process improvements generally achieve limited cost reductions, whereas advanced solvent systems and alternative capture technologies offer greater potential for future cost optimization. Additional barriers, including limited economies of scale, underdeveloped industrial infrastructure, and the lack of standardized techno-economic assessment frameworks, are also discussed. Finally, the paper proposes future research directions to reduce CCS costs and promote its broader industrial application.

Keywords: carbon capture and storage, amine-based absorption, cost reduction, techno-economic analysis, post-combustion capture

1. Introduction

With the global push to achieve a net-zero emission goal, carbon capture and storage (CCS) technology is seen as one of the most important measures to facilitate deep decarbonization. According to the Special Report on Global Warming of 1.5°C published by the Intergovernmental Panel on Climate Change (IPCC), within the next few decades, CCS might provide about 15-30 percent of the total emission cuts [1]; Though the use of CCS has largely been restricted to the

energy sector, it has a massive emission-reduction capability that has encouraged its extension to other difficult-to-abate sectors such as steel, chemical, and cement manufacturing [2]. Such uses underscore the possible use of CCS in reducing emissions of industrial sectors where direct electrification is still problematic.

Nevertheless, the existing implementation volume of carbon capture and storage (CCS) technology is still small in comparison to the volume necessary to reach the global climate targets. By 2024, about 50 large-scale CCS projects have been built and are in commercial operation around the world [3]. Nonetheless, the existing deployment is significantly lower than the level needed in significant climate mitigation scenarios, with estimates projecting that the capacity of CCS needs to grow significantly to provide the emission reductions pathways in line with the goals of the Paris Agreement [4]. Typical projects include the Petra Nova and Kemper County projects in the USA, which have been forced to close or put on hold because they are not profitable; this is indicative of two main issues that have been experienced in scaling up the use of CCS technology; the first is that technological development does not match commercialization, and the second is that CCS is too costly to implement on a large scale due to the high energy requirements and astronomical prices involved. Even though the post-combustion amine-based process, as one of the major processes, has reached a high level of technological maturity and is known to be compatible with the existing equipment, thus, it enjoys wide popularity in the industry, there are still some serious concerns concerning its high energy consumption and an economic burden.

The recent work on carbon capture technologies based on amines has concentrated on certain technical issues such as solvent behavior, regeneration operations and material development.-as an example, the energy-consuming properties of methyl diethanolamine (MDEA) solvents [5], ways of enhancing circulating regeneration [6], and advancements in new adsorption materials [7, 8]. Although these works have provided a strong background to the future investigation of this topic, a widespread absence of overall summarization of the cost structure of the whole process and the interactions of its components can be observed. Because various studies differ in the range of cost calculations, operational circumstances, and the choice of evaluation metrics, comparing the identical cost-reduction strategies is not easy [9, 10]. Hence, this paper takes a cross-disciplinary strategy to synthesize the current information on the cost structure, energy performance indicators, and economic value, and examine the feasibility and limitations of the different emission reduction technologies, with the purpose to offer reference information concerning the progress and mass application of carbon capture technologies.

2. Total-cost chain structure of CCS and the reasons behind the high-costs of amine-based method

2.1. Full-chain cost distribution characteristics

The cost structure of Carbon Capture and Storage (CCS) projects has unique properties, as stated in the academic literature, where the capture stage plays an important role in the overall economic feasibility of the project. As it was shown by Rubin et al., the amine-based absorption process to post-combustion capture can be considered as the most expensive, costing between 60-80 percent of the lifecycle cost of a CCS project [11]. House et al. found through thermodynamic analysis that the energy used in the initial construction and operation of the capture system is greater than the energy that would be needed to transport and store the captured gases [12]. In particular, transportation costs mostly depend on the distance and mode of transport, and sequestration costs are mostly determined by the geological features of the sites and also contain considerable uncertainty, both of

which form a relatively small proportion of the total cost. To reach the target of low overall costs and high efficiency of the value chain as a whole, it is necessary to overcome the challenge of capture technologies and develop their engineering solutions.

The cost structure analysis shows that the overall cost of the capture system consists of two main parts: capital expenditure (CAPEX) and operating and maintenance costs (OPEX). CAPEX mainly covers all the costs incurred to purchase and install important equipment like absorption towers, regeneration units, heat exchanger, and compressors. Conversely, OPEX is mainly driven by the energy consumption used to regenerate solvents. Nonetheless, the role played by various cost elements is still a subject of discussion. According to some researchers, the intense energy use in amine-based capture systems is one of the main reasons why they are economically unfeasible [2]. At the same time, it has been noted in studies of international engineering projects that in small-scale pilot studies, the cost of civil construction and preliminary preparation can be significant as a part of total investment because there is no economy of scale [11].

2.2. The intrinsic root cause of the high costs associated with the amine-based method

The amine absorption process is the most commonly used carbon dioxide capture technology, but it has severe disadvantages as well. Its main drawback is the energy inefficiency that is achieved with respect to energy use: the processes described by methyldiethanolamine (MDEA) need consumption of about 3.8 - 4.2 GJ/t of thermal energy to achieve CO₂ desorption- which is a process that will greatly affect the net power output of a coal-fired power plant and decrease its overall system efficiency by 8-12 percent [5]. In terms of energy conversion, this energy is reaction heat, sensible heat, and latent heat of phase change; moreover, chemical interaction between primary amines and CO₂ is a big challenge to enhance the energy usage of the system as well as overcome the main technical obstacles [11, 12].

Although cost estimates are reported differently in various studies, there are some common influencing factors that have been found across them. According to Jiang et al., a 90 percent decarbonization of a 650 MW supercritical coal-fired power plant would cost around \$63.9 per ton of CO₂ emissions [13]. By contrast, Adu et al. stated that natural gas combined cycle (NGCC) plants have higher emission reduction costs (\$90 to \$120 per ton) in general because of the lower concentration of CO₂ in the flue gas (about 4 percent, as opposed to 12-14 percent in coal-fired power plants), making it harder and more energy-intensive to capture the gas [14]. The results suggest that carbon capture system economics are highly influenced by the value of flue gas CO₂ concentration. The total cost of emission reduction may be greatly affected by changes in capture conditions such as CO₂ concentrations and capture efficiencies.

The procurement cost of equipment and the losses incurred due to degradation of solvent have a considerable effect on the overall economic performance of the system. Even though the absorption tower and regeneration tower are main elements of the system that demand a large initial investment, their high operating costs are because of frequent maintenance induced by the aging of materials, and also, when tested on a small-scale test bench, the lack of economies of scale causes a constant cost per unit of the process [15].

3. Research progress and comparative analysis of low-cost improvement technologies

3.1. Process optimization for cost reduction and its limitations

In order to minimize the energy used in the process of CO₂ regeneration, various methods have been suggested by researchers, including rich liquid diversion, cascade cooling and heat pump integration. According to Oh et al., a high-efficiency flash distillation column can be used as a concentrator to lower the energy usage of CO₂ regeneration to around 3.2 GJ/t, thus saving costs by about 12-15 percent when compared with traditional methods [6]. Although a number of the available methods are already able to save energy by 10-15 percent, they usually do not significantly change the basic efficiency of the current amine-based absorption system, but only make small changes to it [5, 15]. On the other hand, studies on new absorbents have shown that cost savings of over 30% are possible, which underscores the importance and immense opportunities that lie in the creation of new absorbents in the areas of energy-saving measures and emission reduction initiatives.

3.2. Comparison of new solvent cost reduction approaches

The creation of new absorbents is mainly concerned with mixed amines, phase-change solvents and ionic liquids, but these three kinds of absorbents will differ regarding how much cost reduction they can achieve and how advanced they are technologically.

The mixed amine system exploits the synergetic properties of highly reactive primary/secondary amines and low-energy-demand tertiary amines, which not only results in effective CO₂ absorption but also minimizes the energy requirements used in regeneration. Ding et al. had compared three mixed amine systems including PZ/MDEA, PZ/MEA, and MEA/MDEA and discovered that the PZ/MDEA system displayed the most desirable behavior in terms of CO₂ removal and regeneration energy usage. It has been reported that the cost of CO₂ removal by this system is about \$31.43/ton, and its compatibility with other current capture procedures only needs minor adjustments, which makes it possible to be used on a larger scale [7].

The idea of phase-change solvents is founded on the two-phase separation process of liquids-liquids; the amount of thermal energy saved can be large and heating media requirement minimized by regulating the selective permeability of CO₂. It has been said that in a two-phase system made up of bifunctional ionic liquids, the energy consumption needed to regenerate the Zhan group to capture CO₂ was minimized to roughly 2.0 GJ/ton which was almost half the energy expenditure of the conventional MEA approach [16] likewise, Dubois et al. observed that the use of the DEEA-MAPA mixture decreased the cost by some 26.3 percent versus the MEA method [17]. In comparison with more traditional amine absorbents, phase-change solvents have a greater exergy efficiency (up to 48%), but due to their extreme sensitivity to changes in temperature and somewhat severe operating conditions they have a large mass transfer resistance and storage stability issues, which are barriers to their industrialization.

Being a green solvent system with superb characteristics, the ionic liquids have attracted a lot of interest and have shown extensive potential applications because of their extremely low volatility and adjustable properties. Elobaraka et al. discovered that in specific circumstances, some ionic liquids can decrease parasitic power use by over 50 percent relative to conventional MEA systems [18]. Even though this technology has reached considerable development, and it has many benefits, its mass production is limited by various factors, including high viscosity, high cost, and the absence of long-term stability test results; therefore, it is now still at the laboratory research level [8, 18].

When comparing the cost-reduction effects of different absorbent systems, significant differences in the effectiveness of the various methods are observed. In comparison with phase-change solvents, mixed amines and process optimization, ionic liquids have similar or even better potential to reduce costs. Nevertheless, when it comes to the aspect of technological readiness and real-world application, such benefits go together with greater technical risks and uncertainties. It shows that the connection between cost-reduction potential and technological innovation level is not necessarily linear, and economic benefit-technological complexity-scalability trade-off continues to be the critical factor that restricts the development of more advanced absorbent systems and their large-scale deployment.

3.3. Comparative analysis and disagreements regarding alternative techno-economic feasibility

Other non-amineating techniques like solid adsorption and membrane separation are also gaining popularity because they are environmentally friendly and sustainable, but there has been much debate about their economic feasibility over the years. Using a comparative analysis of piperazine absorption, zeolite 13X adsorption, and polymer membranes, Zanco et al. found that more often than not, conventional amine-based absorption is a preferable choice [9]. However, the Micari research team, in a work report on the creation of a highly effective nanoporous graphene membrane, stated that the cost of CO₂ capture with this membrane is estimated at around \$28-\$46 per ton, and that it has better prospects than MEAs [19]. The difference is mainly due to different views on the nature of membrane material (e.g., its flux and selectivity) and the operating parameters of the system; hence, the transition of these new materials to commercial use will necessarily involve numerous challenges and risks.

The technology combines both the benefits of pressure swing adsorption (PSA) as well as membrane separation, and it has significant technical advantages and shows significant potential in application under certain operating conditions. Nevertheless, because of the sophisticated design of its equipment, it requires a large initial investment and a lot of work afterwards to maintain it. In the long run, this technology can be integrated with amine absorption to counterbalance their weaknesses, serve small-scale pollution treatment or low-concentration gas purification, and its area of use is projected to grow slowly but steadily; however, it cannot replace the traditional methods of processes in the near future.

4. Challenges in large-scale implementation and research perspectives

4.1. Constraints on cost reduction

Despite the fact that technological innovations have paved the way to lower costs and improved efficiency in the carbon capture and storage (CCS) industry, the market-oriented implementation is challenged by serious barriers. At the moment, there are no commercial CCS projects on a large scale and this makes it hard to achieve economies of scale; moreover, the wide range of unit investment expenses between the projects of different sizes would also influence the financial sustainability of the entire industry [11]. The very high capital and the operational maintenance costs, combined with a high reliance on government policy, discourage private investment and investment over the long term is not possible [3]. Besides, the difficulties in building CO₂ transportation pipelines and storage plants add to the transaction costs along the whole value chain, and the uncertainty in picking sites to develop infrastructure could further complicate this problem [2, 15].

According to an industrial chain point of view, with the existing market situation, the creation of autonomous storage, transportation, and sequestration capacities of separate projects cannot be enough to optimize the use of resources. By forming regional CCUS (Carbon Capture, Utilization, and Storage) clusters and implementing the hub-and-spoke operating structure, various sources of emissions will have the ability to use the same transportation pipeline systems and storage infrastructure, thus minimizing the initial capital investment and increasing the total system efficiency. The same experiences and challenges have also been observed in other cross-border CCUS development projects. As an example, many European countries, including EU member states or Germany, are starting to abandon single-point project layouts in favour of large-scale cluster partnerships in order to increase overall societal efficiency [2].

4.2. Future research priorities

One of the main reasons why the development of similar research is low is because there are no standardized procedures of carrying out Technical and Economic Assessment (TEA) as shown by a comparative analysis of relevant literature. Existing studies differ widely in terms of how they choose energy consumption levels, costs per unit, capacity factor, and discount rate, which not only does not allow comparing the results of other studies but also easily results in different conclusions [9, 10]. It is therefore an urgent necessity to develop a common TEA standard and build a public data repository to preserve basic data; at the same time, the model needs to be studied over the long term on million-ton-scale demonstration projects with ongoing improvements and modifications of the parameters in the model depending on real data, thus explaining the correlation between benefits brought by technological innovations and the increase in scale of technology [11, 15].

At the moment, research into innovative solvents also encounters a significant number of challenges. In the case of phase-change solvents, there is still no complete understanding about the thermodynamic properties of their phase-separation process and the mechanism of mass transfer-reaction synergy; with ionic liquids, the problem of their low long-term stability and the difficulty in their efficient large-scale production should be solved. They all prevent the use of the same technologies in the industry [8, 17, 18]. Besides, in carbon dioxide geological sequestration, the problems of risk evaluation in long-term leakage, the creation of a management system that includes several stakeholders, and the degree of public consciousness and acceptance of this technology are not only technical concerns but also present some challenges to the progress of the project. All these concerns need theoretical investigation and confirmation.

5. Conclusion

The paper examines, analyses and compares the available domestic and international literature on the techno-economic aspect of CCS technology which results in the following main findings. (1) Cost composition analysis shows that the capture stage is the most expensive step in the overall lifecycle cost, and it can be about 60-80%. Among all the types of costs, capital expenditure (CAPEX) and operating expenditure (OPEX) have the biggest share, whereas transportation and storage expenses are much lower than those of the capture process. (2) The most significant economic problem of amine-based absorption systems is linked to the high energy consumption in the regeneration of the solvent. This energy penalty has a strong impact on the economic viability of the overall CCS implementation. Even though the operational costs can be affected by the variation in flue gas CO₂ concentrations and fuel types, they are usually not as significant as the possible cost savings obtained through increased solvent performance. In particular, different fuel choices may

result in significant cost differences, with some increases surpassing 30 percent in some situations. (3) Available literature suggests that traditional approaches to the process optimization are able to generate low savings, usually less than about 15 percent. By contrast, sophisticated absorbent systems, like mixed amines, can offer higher potentials by decreasing the regeneration energy usage and operational costs, with savings having been reported to be around 20-30 percent. New technologies, such as phase-change solvents and ionic liquids, might have even greater cost reductions of 26-48 percent or over 50 percent in special circumstances. Nevertheless, these technologies are still in the initial developmental phases and have uncertainties in terms of scalability, cost, and long-term performance. Despite the potential benefits of membrane-based separation technologies, their economic performance is highly variable depending on the materials used and working conditions. (4) With respect to the large-scale deployment of CCS, the existing constraints of inadequate economies of scale and absence of standardized technical frameworks indicate that there is a need to develop an integrated pathway using a combination of technological innovation, infrastructure alignment, and policy support. The future work needs to be done on creating a consistent development model starting with fundamental research and ending with million-ton-scale industrial applications, and enhancing techno-economic assessment systems to hasten the transformation of scientific discoveries into practice.

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