Prevalent Hybrid Physical–Chemical Absorption Technologies for CO_2 Capture and Application in China

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Abstract. The atmospheric levels of CO_2 have reached levels never seen before due to industrialization. This highlights the need for scalable, reliable, and economical carbon capture solutions. In this review, the author evaluated hybrid physical-chemical absorption systems. This absorption system combines high capture efficiency from physical solvents and the selectivity of chemical absorption. The major systems reviewed include solvent mixtures, membrane-assisted absorption, solid-supported amines, and desublimation hybrid systems. These were assessed on energy consumption, stability, sustainability, and deployment possibilities. The author concluded that hybrid systems could use 15-30 % less regeneration energy than traditional monoethanolamine-based capture. In addition, the hybrid systems can be produced with increased durability and operational flexibility. As of 2025, China is the world's largest emitter of $CO_2$and therefore represents a strong case study for assessing the pathways for large-scale implementation. The current research indicates strong technical viability but also reveal challenges such as solvent degradation, corrosion risks, and limited scale-up capacity. In conclusion, combining technology progress, technological and economic assessments, and policy frameworks, show that hybrid absorption is a viable and promising path toward decarbonization.

Keywords: CO_2 capture; hybrid absorption; physical-chemical solvents; membrane-assisted absorption; CCUS.

1. Introduction

1.1. Background on CO_2 Emissions and the Need for Capture Technologies

By June 2025, atmospheric CO_2 concentrations reached 430 ppm, a record high for anthropogenic emissions [1]. The increase in CO_2 concentration is a result of fossil fuel combustion in high-emission industries such as steel, cement, petrochemicals, and electricity generation. The global energy industry produced an estimated 36.8 Gt of CO2 emissions in 2022 [2]. The negative impacts on the environment includes biodiversity loss, ocean acidification, and climate change. This has intensified the need for scalable solutions for short-term mitigation.

Carbon capture, utilization, and storage (CCUS) is one of the key factors to reducing emissions in hard-to-abate sectors. This review focuses on the capture step of the CCUS chain, specifically hybrid physical-chemical absorption systems. There is a growing effort to use more renewable energy sources and to make industrial processes more efficient. However, for industries that produce CO_2 as part of their processes, these two actions alone are usually not enough. Capture technologies enable partial decoupling of the carbon emissions from the industrial production and can use existing infrastructure.

1.2. Importance of CO_2 Capture and the Role of Hybrid Technologies

Among the various options for CCUS, post-combustion capture using absorption remains the most favored route. Chemical absorption generally has an effective capture rate, but it is an energy-intensive process, is corrosive, and can result in the breakdown of solvents [3, 4]. Selexol and Rectisol are two physical solvents that do not require as much energy to regenerate, but they must operate under high pressure or high-CO_2 conditions and do not have any chemical selectivity [3, 5].

To make use of both types of solvents, hybrid physical-chemical absorption methods have emerged. The goals for hybrid methods - which use mixed solvents, membrane-absorption

combinations, or solid-supported amines - are to reduce energy requirements for regeneration while not lessening flexibility and absorption capacity. Studies have indicated that conservation rates can reach as high as 20-30% compared to the previous independent MEA systems, characterized by optimal thermal and oxidative stabilities [6-8].

The development of hybrid absorption technologies is particularly relevant for emerging economies with high industrial output. Their ability to be deployed cost-effectively and easily integrated into existing plants makes them more appealing in national plans to cut carbon emissions. They also fit with bigger policy goals such as energy efficiency, material circularity, and net-zero transitions [4, 9, 10].

1.3. Scope and Purpose of the Review

This review provides a summary of current CO_2capture technologies, focusing primarily on post-combustion absorption. The review begins with a summary of the principles, advantages, and disadvantages of the two most widely used absorption methods, i.e physicial and chemical absorption systems, and identifies their main limitations (energy penalties and selectivity or degradation) as two significantly different sets of limitations. The author devotes the bulk of his review to hybrid physical-chemical absorption systems. These systems are designed to combine the better energy efficiency of physical solvents with the reactivity (living mussel moment) and selectivity of chemical agents (solvents). The review deals with four different types of hybrids: solvent blends; membrane-assisted absorption; solid-supported amines; and based on desublimation. Each shown based on its performance in terms of energy consumption, material stability, and scalability.

The review also uses China as a case study to examine how hybrid systems are being implemented at scale in industrial settings. Being a major emitter with significant investments in CCUS, China offers insight into the integration of hybrid technologies within decarbonization policies and industrial infrastructures [11].

Although previous reviews have covered either physical or chemical absorption systems, few have analyzed hybrid configurations in terms of performance, possiblility to implement, and regional policy alignment. The goal of this review is to fill that gap by gathering recent findings and identifying key challenges specific to hybrid absorption technologies.

2. Overview of Carbon Capture Technologies

2.1. Physical Absorption

Physical solvents like Selexol and Rectisol desorb CO_2 due to differences in partial pressure, not experiencing chemical reaction with the gas. Such technologies are particularly suitable for pre-combustion applications where gas streams are high pressure, like integrated gasification combined cycle (IGCC) systems or hydrogen generation plants. Since there is no strong chemical bonding, regeneration energy of physical solvents is quite low, ranging between 1.0–1.5 GJ t^{-1} CO_2 [12, 13], with some studies reporting around 1.2 GJ t^{-1} CO_2 depending on particular process design and operating conditions. In addition, the solvents are stable as well as not corrosive. This lowers the costs and keeps solvent losses to a minimum. However, when the CO_2 partial pressure is low, this system is not effective, so they are not viable for capturing CO_2 from flue gases at atmospheric pressure after combustion [14].

2.2. Chemical Absorption

Absorption-based chemical technologies utilize solvents like monoethanolamine (MEA), ammonia, or amino acid salts that form stable chemical bonds with CO_2. These systems work very effectively and can capture greater than 90% of the carbon dioxide that comes out of the combustion process, which is the reason they are the most common way to do so [15]. However, it takes a lot more energy to regenerate the solvent and get pure CO_2 out than it does to physically absorb it. The energy needed for this process is usually between 3.0 and 4.0 GJ/ton CO_2, with MEA usually being

3.6 GJ/ton CO_2 [16, 17]. Factors such as corrosion, solvent degradation, and losses during operations all make long-term stability worse. These factors raise operating costs and make it harder to scale up without new technology [17].

Table 1. Comparison of CO_2 Absorption Technologies

Technology	Energy Use (GJ/t)	Selectivity	Stability	Cost Efficiency
Physical Absorption	1.0-1.5	Low	High	Medium
Chemical Absorption	3.0-4.0	High	Low	Low
Hybrid Systems	1.8-2.5	Medium-High	Medium	High

Based on both simulation calculations and pilot-scale results reported in recent literature, these comparative values, which are shown in Table 1, represent a broad consensus [18, 19]. In order to improve the balance between energy consumption and capture efficiency, hybrid systems, which combine or integrate physical and chemical absorption mechanisms within staged configurations, are receiving more and more attention. Aqueous ammonia systems and the combined Selexol–Sulfinol processes are two examples that raise the CO_2 loading capacity by lowering regeneration heat demand towards intermediate values.

3. Hybrid Absorption Technologies

Hybrid absorption technologies integrate physical and chemical capture mechanisms to enhance CO_2 selectivity, reduce regeneration energy, and extend process stability under varying industrial conditions. Traditional chemical absorption systems like MEA require significant thermal input for solvent regeneration and suffer from degradation and corrosion. Hybrid systems combine solvents, membranes, or solid carriers to enhance important features. These systems can achieve high CO_2 loading, reduce the energy needed for reboiler operations, and improve cyclic stability. These systems effectively capture carbon dioxide (CO_2) by combining two key elements: the ability of solvents to dissolve CO_2 well and the selective features of membranes or sorbents. This combination helps them achieve a good balance between capturing CO_2 efficiently and meeting energy requirements [5, 20, 21].

The underlying principle is to exploit complementary mass transfer and phase interaction mechanisms. For example, combining a physical membrane (which offers low-resistance pre-concentration) with a reactive solvent (which selectively captures CO_2) creates a multi-stage barrier against undesired gases and minimizes downstream energy demand.

3.1. Solvent Blends

Solvent blending is one of the most explored hybridization strategies. Conventionally, MEA-type solvents were regenerated at higher temperatures (about 120°C) and were more likely to break down from heat and oxygen. Solvent blends, like MEA-ammonia or amine-oxide blends, have lower regeneration enthalpy, better thermal resistance, and less chance of corrosion because the vapor-liquid equilibrium and buffered pH profiles of the binary systems are different [6].

MEA-ammonia solutions are especially good because ammonia does not require a high amount of heat to regenerate and MEA reacts quickly. Oxidation-type amines, like AMP–MDEA systems, are also helping to reduce volatility losses. Compared to pure MEA systems, these systems can save up to 20% on energy, which makes them very easy to retrofit with installed amine scrubbers with little need to modify the process [6].

3.2. Membrane-Absorption Hybrids

Membrane-absorption hybrids combine physical separation (via selective membranes) with chemical absorption (via reactive solvents) to form a two-step process. Membranes serve as a pre-concentration unit, enriching CO_2 from flue gas prior to contact with solvents. This lowers the

solvent's CO_2 load per unit volume, thereby reducing solvent circulation rate and thermal duty downstream [7].

Such configurations enable compact plant design and modular scale-up, particularly valuable for industrial applications with space and cost constraints. Studies show that membrane-assisted capture systems can cut overall energy demand by up to 28% versus traditional chemical absorption alone [7].

These systems also exhibit strong potential for integration into modular and compact plant designs, and have been proposed for retrofit and greenfield applications across multiple sectors. Earlier reviews had already identified the promise of membrane-assisted chemical absorption for reducing energy penalties and solvent circulation rates in post-combustion systems [7, 21].

3.3. Solid-Supported Amines

This category immobilizes liquid amines on high-surface-area solid matrices such as silica, metal-organic frameworks (MOFs), or mesoporous polymers. The hybridization lies in preserving the chemical selectivity of amines while leveraging the low-pressure drop, structural integrity, and reusability of solids [8].

Solid-supported amines are especially effective under pressure swing conditions or when used in dual-stage systems-for example, pairing physical high-pressure capture with medium-pressure thermal desorption. Modeling by Huang et al. revealed 18% energy savings using such configurations compared to conventional chemical absorption alone [8].

3.4. Desublimation/Pressure-Swing Systems

Desublimation-based hybrid systems separate CO_2 by converting it directly from gas to solid at cryogenic temperatures and high partial pressures, often with assistance from cryogenic or pressurized streams. When combined with chemical absorption phases or in pressure swing adsorption (PSA) cycles, the systems provide selective CO_2 recovery at higher purity with lower solvent degradation [9].

Pilot-scale tests in Canadian steel mills showed that desublimation outperforms MEA systems in both capture efficiency and operational cost, due to the avoidance of solvent recycle and water recovery steps [9]. These are especially appropriate in process gas streams of high partial pressures of CO_2, i.e., steel or cement plants.

There are many hybrid configurations that demonstrate good energy savings in the laboratory; however commercialization remains inconsistent. For instance, solvent blends with either AMP or MDEA, are close to TRL 7, while membrane−absorption hybrid systems are ranged TRL 4−6 depending on membrane fouling etc. The heterogeneity of TRL level is a product of both materials and integration difficulties to be addressed for commercial rollout [22].

4. Economic and Technical Challenges

4.1. Energy Penalties and Solvent Regeneration

The energy penalty remains one of the most significant barriers to widespread deployment of solvent-based CO_2 capture. When using amine solvents (such as MEA) in systems, the regeneration of the solvent requires a substantial thermal input-typically between 3.0 and 4.0 GJ/ton of CO_2 captured. This energy is mainly used to break the chemical bond between CO_2 and the solvent. This process can lead to a 25–30% decrease in the net power output of power plants that use post-combustion capture [16, 17]. Researchers are looking for alternative solvents and ways to improve processes, like using advanced stripping technologies or hybrid solvents, to reduce negative impacts. However, current challenges in reaction speed, solvent costs, and complexity limit how these solutions can be used effectively [10, 23].

4.2. Solvent Stability and Equipment Corrosion

Most amine-based systems are subject to degradation through thermal and oxidative pathways over time. Such reactions generate byproducts like heat-stable salts, aldehydes, and nitrosamines. These lower the performance of the solvent and raise operating expenses. In addition, solvent deterioration usually causes severe corrosion of equipment, particularly of carbon steel. This requires costly corrosion inhibitor or more resistant alloys [16, 17]. The high oxygen content and trace metals of the flue gas also contribute to the acceleration of degradation. Recent reports state that despite the use of additives, long-term contact causes severe losses of solvent quality and increased waste handling expense [10, 23].

4.3. Cost Analysis and LCA

The life-cycle cost (LCC) of employing solvents for CO_2 capture relies heavily upon the amount of solvent used, the amount of energy used and the amount of maintenance necessary due to corrosion. The LCC estimates for MEA-based capture technologies are between \$58 and \$120 per ton of CO_2 avoided, depending largely on how it is implemented in a power plant and its energy source [13, 14]. From a life-cycle assessment (LCA) framework, the solvent degradation and energy use for the regeneration of solvents have significant global-warming potential (GWP) and acidification potential (AP) [4, 24]. Zhang et al. (2020) demonstrate that post-combustion amine scrubbing is one of the most sophisticated technologies but its environmental and economic viability depend heavily on improvements in solvent design and recovery of waste and integration of heat [24].

Recent LCA studies like Zhang et al. (2020) showed that hybrid MEA-ammonia systems achieved a 25% reduction in GWP over the pure MEA system. Lower energy consumption and less material degradation led to better performance. However, solid-supported amines resulted in a higher potential for eutrophication during material synthesis, highlighting a trade-off [25].

5. Case Study: Viability and Outlook of CCUS in China

China has pledged carbon neutrality by 2060, with CCUS becoming the cornerstone of its industrial decarbonization strategy. China has about 40 pilot and demonstration CCUS schemes by 2023, with a total capture capacity of some 4 $MtCO_2$/year, which is a modest number given its emissions (~10.2 $GtCO_2$/year) [25, 26]. State efforts such as green bonds, national demonstration centers, and the inclusion of CCUS within the carbon trading framework have been supportive, but scales are significantly less than required to get China on track with 2060 targets. Capture capacity needs to grow at least 100 times by 2035, with at least 400 $MtCO_2$/year, if mid-century targets are to be achieved.

Technologically, CCUS is feasible across China's energy and heavy industry applications, such as coal-fired power, cement, steel, and ammonia production. The Sinopec Qilu–Shengli CCUS demonstration, which has been online since 2021, captures 1 $MtCO_2$/year by enhanced oil recovery (EOR), proving technical feasibility and integration with domestic oil fields [11]. The majority of ongoing projects employ amine-based chemical absorption, with energy penalties of 3.0–4.0 GJ/ton CO_2 and capture costs of \$58–120/ton depending on sector and region [10, 16, 24]. Nevertheless, hybrid technologies are also becoming prevalent in China's CCUS industry. Pilot-scale demonstrations, such as AMP–MDEA solvent blends at Shanxi coal-fired power stations and membrane–absorption integration studies at Jiangsu's cement industry, have achieved reduction of regeneration energy up to 1.8–2.5 GJ/ton CO_2 and solvent stability enhancement [8, 23, 26]. Energy efficiency has been enhanced by 10–15% by hybrid solvent schemes and by heat integration relative to standard MEA schemes, but solvent degradation and high corrosion rates are ongoing challenges [8, 16].

6. Conclusion

Hybrid absorption technologies combine physical and chemical properties of solvents to capture carbon dioxide (CO_2). These technologies offer a good balance of effectiveness, selectivity, and energy efficiency. By using both types of absorption, they efficiently separate CO_2 while keeping energy use low. Even though the chemical absorption method using MEA remains the standard process due to its maturity in the market, it faces some challenges. These challenges include high energy costs for revamping, solvent breakdown under commercial conditions, and increased operational costs during long-term use. Hybrid configurations address these issues by combining physical solvents with high absorption and low vapor pressures while also benefiting from the chemical solvents' high selectivity and binding capacity. As a result, studies show consistent energy savings of 15-30% in regeneration costs, better solvent tolerance, and more flexible processes. They will benefits applications both pre-combustion and post-combustion processes with hybrids being especially impactful in China's heavy application industries such as in cement, steel, and power generation commitments. A number of pilot applications are emerging across the Country where technical deliverability is evident, however, the current capture capacity is at 4 $MtCO_2/y$. The figure outlines the gulf between existing capability and China's very ambitious target of 400 $MtCO_2/y$ capture by 2035. Therefore, the gulf can only be addressed by hybrid absorption technologies that can be scaled to alleviate existing and persistent inhibitions of solvent corrosion, fouling and limited lifetimes under commercial conditions. Additionally, their employment will be critical in hard-to-abate industries' hard carbonization that cumulatively account significantly of national emissions, especially with China's carbon neutrality by 2060 commitment. Future research should concentrate more on low-regeneration-enthalpy solvent design, membrane anti-fouling strategies, modular hybrid reactor design, lifecycle solvent recovery, and policy-influenced deployment schemes with the objective of accelerating industrial retrofitting and national application.

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