Techno-Economic Analysis of Carbon Capture Technologies for Coal-Fired Power Plants

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Abstract

The increasing concentration of carbon dioxide (CO_2) in the atmosphere poses a significant threat to the environment, contributing to global warming and rising sea levels through the melting of ice caps and glaciers. A major source of CO_2 emissions is the burning of fossil fuels in power plants, which release large quantities of greenhouse gases. To mitigate these effects, carbon capture technologies have emerged as a potential solution to reduce CO_2 emissions before they are released into the atmosphere. However, while effective, carbon capture comes with challenges, including high costs and high energy consumption, which can impact the feasibility of widespread implementation. This review paper evaluates various carbon capture technologies, analyzing their efficiency and cost-effectiveness in coal-fired power plants in order to determine the most viable approach for reducing CO_2 emissions.

Keywords: Carbon Capture, CO_2 emissions, Amine scrubbing

Introduction

Carbon dioxide is a potent greenhouse gas and a primary contributor to global warming. In 2023, the US released 1,532 million metric tons of CO_2 into the atmosphere, and coal-fired power plants represented 46% of these emissions.[1]

Given that coal-fired power plants represent a large fraction of CO_2 emissions, there is significant interest in capturing emissions from coal-fired power plants to reduce the impacts of global warming. There are a variety of technologies for capturing CO_2 emissions from coal-fired power plants, including metal-organic frameworks (MOFs), amine scrubbing, membranes, cryogenic sublimation, zeolites, ionic liquids, and charged sorbents.

Amine scrubbing is currently the most widely used technology for carbon capture. Amine scrubbing involves capturing carbon in an aqueous solution of amine at low temperatures and then regenerating the amine at high temperatures (100-110 °C), releasing pure carbon dioxide.[3]

Moving on, cryogenic carbon capture (CCC) is a process where power plant emissions are cooled to 175 K, solidifying CO_2 from the emissions.[4] Solid CO_2 is then sublimated and sequestered.

Metal-organic frameworks (MOFs) are highly porous materials constructed from a combination of an organic ligand with a metal ion node.[2] MOFs can be used to absorb CO_2 emissions from coal-fired power plants through absorption/regeneration cycles, but so far these have limited practical application due to the MOFs lacking long-term chemical and thermal stability especially under humid conditions.

Charged sorbents are low-cost activated porous carbons with inserted ions as sites for CO_2 adsorption.[5] And zeolites are porous silicates that contain sites for adsorbing CO_2 with high selectivity.[6] Finally, ionic liquids are salts with melting temperatures below room temperature with a high capacity for absorption of CO_2.[7]

Membranes are selective barriers that can separate CO_2 from gas, which is often used in high CO_2 concentration situations like natural or coal gas processing. This technology allows CO_2 to pass through the membrane materials while retaining the other gasses. However, their effectiveness gets challenged due to the low concentration of CO_2 in flue gas, needing large amounts of energy to separate CO_2 effectively.

The carbon capture technologies just described work either as absorbents, adsorbents, or separators. Absorbents and adsorbents refer to similar yet distinct classes of materials that involve the capture of CO_2 within the structure of the material that requires regeneration.

Absorbents are dissolved in a liquid and require CO_2 to dissolve into the liquid and chemically react to capture carbon. In contrast, adsorbents are solids where CO_2 becomes physically trapped on the surface of the material. Technologies like amine scrubbing and ionic liquids function as absorbents.[3] Meanwhile, technologies like metal-organic frameworks, zeolites, and charged sorbents work as adsorbents.

Given that both absorbents and adsorbents involve physical or chemical interaction of CO_2 within the capture material, over time the material becomes saturated with CO_2 and eventually can capture no additional CO_2. To restore the capacity of the material, a regeneration step is required which typically involves heating the material to release CO_2. The released CO_2 is then sequestered. Separators refer to technologies that separate and concentrate CO_2 from other compounds like water. Unlike absorbents or adsorbents, CO_2 is not captured within the material making up a separator and thus does not require regeneration. Technologies such as membranes and cryogenic carbon capture (external cooling loop cryogenics) work as separators.

After CO_2 separation by a separator, the CO_2 is sequestered. This paper does not discuss sequestration in detail, but instead will focus on evaluating the energy penalty and cost of operation of various adsorption, absorption, and separator technologies for capturing carbon pre-sequestration.

Comparison of Technologies

Each technology has advantages and disadvantages. Important considerations for carbon capture technologies include cost efficiency, environmental compatibility, and selectivity for CO_2.

To expand, cost efficiency is described as how much it costs to capture each unit of CO_2. This is measured by dollars per ton of CO_2 captured. For example, Amine Scrubbing has a $52 operational cost per carbon captured ($/ton CO_2). This is important because cost efficiency determines the economic feasibility of a carbon capture technology so that plant operators can justify the investment to integrate carbon capture in their processes.

Furthermore, environmental compatibility can be decribed as how well a carbon capture technology integrates with, and minimizes harm to the environment. For example, this includes factors such as chemical toxicity of the materials used, production of pollutants, and lifecyle impacts on ecosystems. Considering this factor is extremely important as a technology with high environmental compatibility should have safe non-toxic solvents, less harmful pollutants, and use less natural resources, which makes it more sustainable over time.

Selectivity for CO_2 can be described as how preferentially a carbon capture process captures CO_2 compared to other components in a gas stream like nitrogen or water vapor. For example, in adsorption-based systems, zeolites' selectivity is determined by measuring and comparing the amount of CO_2 adsorbed and other gases such as nitrogen. This is important to consider in a technology, as a highly selective material will separate CO_2 much more easily compared to others, reducing both energy consumption and requirements to process the technology.

And finally, a major variable is the energy penalty. This is one of the primary metrics for quantifying the performance of carbon capture technologies and is defined as the extra energy required to operate a system for capturing carbon dioxide emissions. It is reported as a percent of the total power plant energy output.

For example, the carbon capture technology Ionic liquids has an energy penalty of 30% meaning that 30% of the power plant's output is consumed by the carbon capture process only, and only 70% of the plant's original energy output available for its primary purpose. This factor is extremely important when interpreting a technology, as a higher energy penalty means that more of the plant's generated energy is diverted to just run the capture system and this leaves less electricity for use. As a result, this reduces net power output, affects plant economics, and increases operating costs.

As previously mentioned, carbon capture technologies are clustered on the basis of mechanism of capture, categorizing technologies into three mutually exclusive classes: adsorbers, absorbers, or separators. The three different classes of capture technologies use different metrics to compare performance due to differences in operation and technology. However, all three classes can use the same energy penalty metric to compare the quantity of energy needed to capture carbon.

Separators

Seperators isolate and concentrate CO_2 from other gases like nitrogen and do not require regeneration since CO_2 is not stored in the material. Important metrics for comparing carbon capture separators include operational cost per ton of captured CO_2, operational lifetime, capital cost, and energy penalty. Cryogenic carbon capture cools the power plant emissions, causing CO_2 to solidify and is then sublimated and collected. This method is very effective with a 99% capture efficiency and recycles the cooling liquid without relying on expensive chemicals. However, cryogenic carbon capture has an energy penalty of 15% and requires high operation pressures to prevent CO_2 frost.[8] The cost per ton of CO_2 captured ranges from \$55 to \$130 per ton of captured CO_2.[8,9]

Membranes, on the other hand, are cheaper, costing \$35-\$46 per ton of captured CO_2 and have minimal space requirements.[10] Membrane processes do not release harmful byproducts and often don't require modifications to the existing plants.[10] Nevertheless, membranes have a limitation in their thermal, chemical, and mechanical stability: they can degrade in harsh flue gas conditions, suffer wear from pressures, lose efficiency at high temperatures which reduce the long - term reliability of this carbon capture technology.

Adsorbers

While separators focus on physically isolating CO_2, adsorbers provide an alternative approach by selectively binding CO_2 to solid materials. Key factors to evaluate in adsorbers include their selectivity for CO_2, cost per ton of CO_2 captured, energy required for regeneration, and their adsorption capacity. Metal-organic frameworks (MOFs), a type of adsorber, are porous materials with excellent selectivity of CO_2 over nitrogen. However, MOFs do not perform as well in humid conditions as water competes with CO_2 for the same adsorption sites. Drying flue gasses is an option to resolve this issue, but is costly. Thus, current research is focusing on improving water-resistent MOF designs.[2]

Metal-organic frameworks have an energy penalty of 32% - 40% and an operational cost of \$91 - \$147 per ton of CO_2 captured, making them not very economically friendly currently. Zeolites offer a more affordable alternative and these porous silicates also have high CO_2 selectivity and cost only \$24 - \$42 per ton to operate. Nevertheless, like metal-organic frameworks, Zeolites struggle in humid conditions and also have higher energy requirements for regeneration.[6] Charged sorbents, a new technology, uses porous carbon with embedded ions to attract CO_2. These materials are able to regenerate at very low temperatures and are powered by renewable electricity making it a very energy-efficient option. They have an energy penalty of 6% and a cost range of \$18 - \$56 per ton.

Absorbers

Absorbers dissolve the CO_2 into a liquid which is then consequently followed by a chemical reaction, the liquid is then regenerated to release CO_2. Key evaluation factors to consider for absorbers include CO_2 capture capacity, selectivity, regeneration energy, cost, and environmental impact. Till now, Amine scrubbing is the most mature and widely used CO_2 capture method. This process involves capturing CO_2 in an aqueous amine solution at low temperatures and then it regenerates the amine at 100-110 ℃ to release pure CO_2.

Amine scrubbing has an energy penalty of 20-30% and an operational cost of \$52 per ton.[3] However, this capture technology faces challenges such as solvent degradation, high thermal energy use, and the materials corrode over time. Ionic liquids is an alternate capture technology that is regenerated at much lower temperatures of 50-70 ℃. Additionally, this technology is thermally stable and can reduce degradation issues. However, Ionic liquids are highly viscous particularly at high concentrations of CO_2 and extremely expensive with an operational cost of \$90 - \$275 per ton of captured CO_2. Despite having a good regeneration profile, this technology has an energy penalty of 30% and this high cost limits is widespread use.

Carbon Capture Technology	Energy Penalty (%)	Operational cost per carbon captured ($/ton CO2)	Reference
Ionic Liquids	30	90-275	Ref:[7]
Cryogenic Carbon Capture	15	55-130	Ref:[8,9]
Amine scrubbing	20-30	52	Ref:[3]
Molten/Charged sorbents	6	18-56	Ref:[11]
Metal-organic frameworks	32-40	91-147	Ref:[12]
Zeolites	24-26	24-42	Ref:[13,14]
Membranes	20-30	35-46	Ref:[15]

Figure 1: Comparison of Carbon Capture Technologies: Energy Penalty and Operational Cost and references

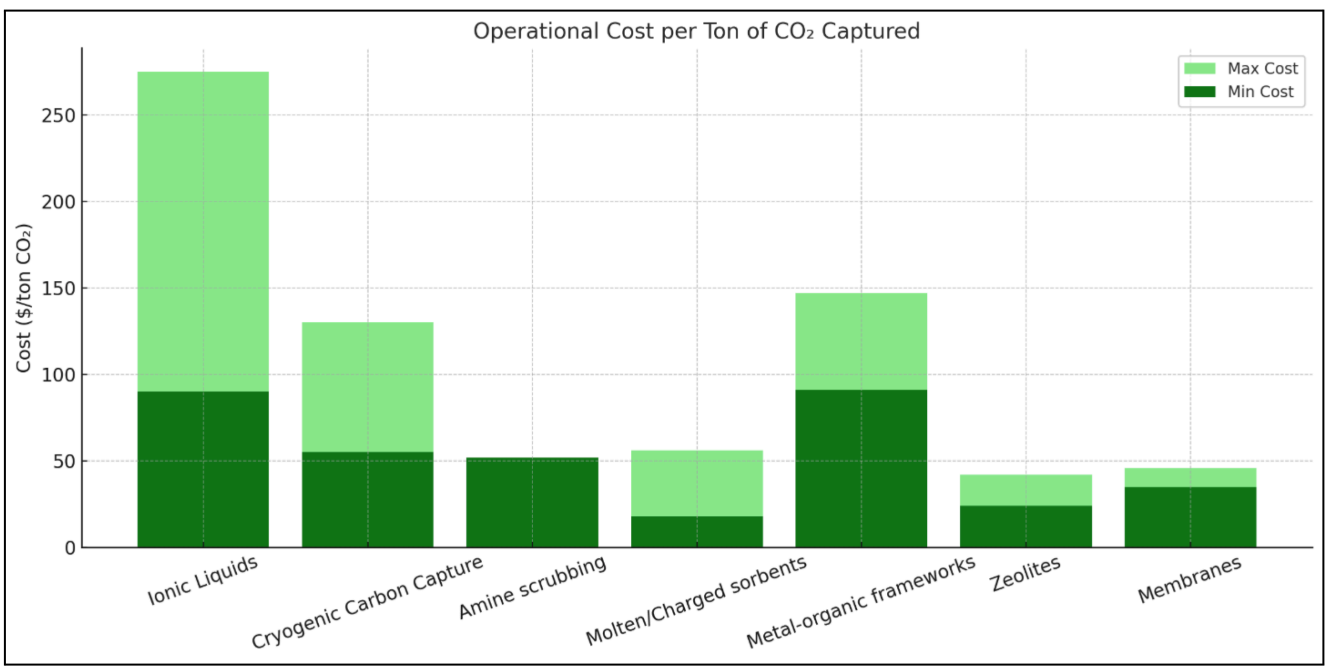

Figure 2: Operational Cost per ton of CO2 Captured

Current State of the Art

Based on the table above with all the listed technologies, it is clear that the technology of Amine scrubbing is best for carbon capture to reduce emissions, which helps illustrate why it is also the most widely used technology. Additionally, while charged sorbents have a lower energy penalty, their high operating cost (50% greater than amine scrubbing) currently limits large-scale adoption. Future research should focus on optimizing material durability in ionic liquids, reducing the energy consumption of cryogenic carbon capture, and developing cost-effective alternatives to amine scrubbing.

Finally, Amine scrubbing has around the same energy penalty compared to other technologies, if not less, but the cost per ton to capture is significantly lower compared to others. Taking these into consideration, Amine scrubbing is the best technology for carbon capture.

Conclusion

In summary, this paper explored various carbon capture technologies, evaluating their efficiency, cost, and feasibility in reducing CO_2 emissions from power plants. Among the technologies analyzed—adsorbents, absorbers, and separators—amine scrubbing stands out as the most practical and widely used solution due to its high capture efficiency, established industrial application, and relatively lower cost per ton of CO_2 captured. However, despite its advantages, amine scrubbing still faces challenges such as energy penalties and solvent degradation, which future research should aim to improve. Additionally, more research should be conducted on emerging technologies like charged sorbents and cryogenic carbon capture, which show promise in reducing energy costs and improving sustainability but require further development before large-scale implementation. Advancements in material science and process optimization will be essential in refining these technologies, ensuring carbon capture becomes a more cost-effective and scalable solution in the fight against climate change.

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