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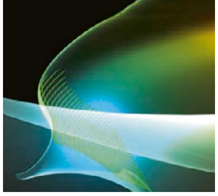

COMMENTARY

Atmospheric alchemy: The energy and cost dynamics of direct air carbon capture

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ABSTRACT

With atmospheric CO_2 exceeding 420 ppm, the clock is ticking on the climate crisis. DAC offers a revolutionary approach to directly remove this excess CO_2, acting as a critical tool in our fight for a sustainable future. However, current DAC systems face the challenge of high energy consumption. Continuous fan operation for air intake and sorbent material regeneration, consuming nearly 2000–3000 kWh per ton of CO_2 captured, are major contributors. Optimizing these processes is crucial. Advancements in sorbent efficiency, system design that minimizes parasitic energy losses, and seamless integration with renewable energy sources are key to slashing DAC's energy demands. By reducing its carbon footprint and enhancing economic viability, these advancements can unlock the full potential of DAC to become a game-changer in combating climate change and securing a cleaner future for our planet.

Amid a relentless global climate crisis, the 28th Conference of the Parties (COP28) spotlighted Direct Air Carbon Capture (DACC) as a key intervention to mitigate escalating temperatures and CO_2 levels. The Intergovernmental Panel on Climate Change (IPCC) underscores the urgency of this challenge, stipulating the need for robust CO_2 removal strategies. It sets a daunting yet crucial target: capture 85 million metric tons of CO_2 by 2030, escalating to 980 million metric tons by 2050, to achieve net-zero emissions (IEA, Executive Summary—Direct Air Capture 2022—Analysis. https://www.iea.org/reports/direct-air-capture-2022/executive-summary). Despite this imperative, the existing 19 operational DAC facilities globally face significant barriers, including prohibitive costs and stringent regulations, which impede their large-scale application (Ozkan et al.). Current status and pillars of direct air capture technologies. Iscience (2022). While COP28 stopped short of delineating a definitive roadmap for DAC, this article addresses a vital aspect of this technology: DAC processes' substantial energy and heat requirements, which are integral to their operational efficiency and economic viability. This article illuminates pathways for future technological evolution and cost optimization through an in-depth analysis of these requirements, thereby charting a course toward a more effective and scalable DAC infrastructure.

Keywords absorption · absorbent · carbon dioxide · environment · environmental impact

Discussion

- Given the significant energy and heat requirements of DACC processes, what technological innovations are necessary to make these systems more energy efficient and economically viable? Considering the substantial energy demands of DACC processes, what are the most promising avenues for reducing these requirements to enhance the technology's scalability and cost-effectiveness? How can current technological limitations be overcome to scale up DACC effectively? What role could renewable energy sources play in meeting the energy and heat demands of DACC facilities, and how might this integration impact the overall carbon footprint of the carbon capture process? How do the energy and heat requirements of DACC technologies influence their location and infrastructure needs, particularly in relation to energy sources and heat sinks? What technological innovations or advancements are currently being explored to optimize the energy and heat efficiency of DACC processes, and what challenges do they face in terms of implementation and scaling? Given the significant role of DACC in achieving net-zero emissions targets, how can policy and regulatory frameworks be designed to support the development and deployment of energy-efficient DACC solutions?

Introduction

Direct Air Capture (DAC) emerges as a powerful weapon in the escalating battle against climate change. This burgeoning technology actively intercepts atmospheric CO_2, offering a potential pathway to mitigate anthropogenic emissions and stabilize Earth's climate. However, DAC operation remains intricately intertwined with energy consumption, with each stage of the capture process demanding substantial resources. From the initial intake of air fueled by voracious fans to the heat-intensive regeneration of CO_2-laden sorbents, energy flows through the system like a potent yet demanding lifeblood. Initially, fans draw atmospheric air into the system, consuming a significant portion of the DAC's total energy to maintain airflow across CO_2-capturing sorbents. This fan energy use can range from 300 to 900 kWh per ton of CO_2 captured. The sorbent material, central to DAC technology, chemically binds to CO_2 molecules. Once saturated, it undergoes an energy-intensive regeneration phase requiring thermal energy, accounting for a substantial portion of the DAC plant's total energy consumption. The energy demand for solvent regeneration varies based on the solvent material and the efficiency of the process.[1–3] Optimization strategies in regeneration methods and airflow designs can significantly reduce energy consumption, enhancing the overall sustainability and efficiency of the DAC system.

The International Energy Agency (IEA) reports that as of 2022, there are 18 operational direct air capture (DAC) facilities across Canada, Europe, and the USA. Moreover, the first large-scale DAC plant, which can capture up to 1 million tons of CO_2 per year, is in advanced development and is expected to be operational in the USA by the mid-2020s. This is part of a broader effort to scale up DAC technologies in line with net-zero goals.[4]

Ozkan et al. provide insights from industry and academia on the expansion of DAC projects.[5] It notes that 27 DAC plants are commissioned and 19 completed globally, with a combined capacity of removing about 11,000 tons of CO_2 annually. The U.S. invests heavily in this technology, aiming to create large-scale DAC hubs. The discussion includes the importance of using low-cost, low-carbon energy technologies for DAC and highlights the potential cost-effectiveness of geothermal power compared to solar power. Operational costs are suggested to be manageable at less than 1% of global GDP. The article also discusses the modular design of DAC systems and anticipates cost reductions with scale, with potential costs as low as \$25 per ton of CO_2.[5,6]

Young et al. evaluate the economic viability of Direct Air Capture and Storage (DACS) technologies, projecting that while costs can significantly decrease to \$100–600 per ton of CO_2 by 2050 through strategic deployment, achieving the more optimistic target of \$100 per ton is unlikely without substantial policy support.[7] The study emphasizes the importance of aggressive deployment, tailored policy mechanisms, and the need for a pragmatic approach to siting and technology selection to reduce costs and enable DACS to contribute effectively to climate mitigation efforts.

Herzog discusses the costs associated with Direct Air Capture (DAC) technologies.[8] It mentions the only "real" cost number available for negative emissions from DAC is \$1200 per ton of CO_2, as priced by Climeworks for their facility in Iceland. The literature on DAC costs is fragmented, showing a wide range of estimates from \$20 to \$1000 per ton of CO_2. Fuss et al. narrow this range to \$100–300 per ton of CO_2 but suggest that initial costs for a first-of-a-kind plant might be around \$600–1000 per ton of CO_2, potentially decreasing as technology advances.[9] However, there is no guarantee costs will decrease to the lower end of the estimate. The document emphasizes the variability in DAC costs depending on several factors, including location, fuel costs, and capital costs, making it challenging to generalize or predict exact numbers for DAC implementation on a larger scale.

But this intricate dance holds its secrets. Can we refine the steps, lighten the energy burden, and make DAC a sustainable symphony? This paper delves into DAC's complex choreography, meticulously dissecting each phase's energy demands. Dissect the air intake process, where optimized fan technology and airflow designs are key to reducing the excessive energy burden. Unlocking the secrets of sorbent regeneration, revealing alternative methods and promising materials that minimize the reliance on thermal processes. Finally, this article examines the often overlooked final act, CO_2 compression, where strategic pressure selection and renewable energy integration offer avenues for significant energy savings.

Beyond mere analysis, this paper envisions optimization strategies. Exploring innovative sorbent materials with heightened CO_2 affinity and lower regeneration requirements. Delving into hybrid capture methodologies that synergistically combine different technologies for enhanced efficiency. Advocate for integrating renewable energy sources, transforming DAC into a beacon of climate mitigation and sustainable energy utilization.

This comprehensive exploration illuminates the path toward a future where DAC transcends its energy-intensive infancy. By optimizing each step, embracing technological advancements, and harnessing the power of renewable energy, unlocking the full potential of this transformative technology. In doing so, one can orchestrate a more sustainable future where DAC becomes a technological marvel and a pivotal instrument in the symphony of climate action.

Understanding the energy consumption of DAC systems

DAC systems are at the forefront of technological advancements for mitigating climate change by actively removing CO_2 from the atmosphere. These systems are multifaceted, involving several energy-intensive steps to maintain continuous operation. Ozkan et al. provide a detailed depiction of the carbon capture process for both liquid and solid sorbents through a Bloch diagram, which includes the energy consumption levels at each stage of the process.[2]

The initial stage utilizes fans to draw atmospheric air into the system. These fans are essential to the process, ensuring a consistent airflow across the sorbent materials that capture CO_2. The energy consumption for this step is considerable, as the fans must operate without interruption to maintain the necessary airflow, which can account for a significant portion of the DAC system's total energy usage. According to Thunder Said Energy, a DAC plant may need to move approximately 3000 tons of air per ton of CO_2 captured.[10] In other words, to capture 1 GT of CO_2 in one year, a DAC system must process at least 34 trillion cubic meters of air per year or 25 million cubic meters per second. The energy consumption of fans in DAC plants can range from 300 to 900 kWh per ton of CO_2 captured. This represents a significant portion of the total DAC system energy usage, often between 20 and 40%.[4] A study of the Climeworks Orca plant in Iceland estimated fan energy consumption at around 370 kWh per ton of CO_2 captured.[11,12]

Another study on a hypothetical DAC plant using high-efficiency fans suggested a potential reduction to 230 kWh per ton.[13] It indicates that improved fan efficiency and alternative airflow designs could reduce fan energy consumption to around 230 kWh per ton of CO_2 captured, highlighting the potential for optimization. Furthermore, another study demonstrates that using low-pressure blowers in conjunction with packed beds can lead to a reduction in fan energy consumption of up to 50% compared to traditional high-pressure fan systems.[14]

Erans et al. discuss advancements in DAC technologies, specifically the trend toward using structured contactors, like monoliths or films/sheets, to address challenges associated with high-pressure drop in packed beds.[15] Parallel channel cellular monoliths are highlighted for their ability to offer low-pressure drops and high mass transfer rates, with considerations, including cell density, wall thickness, and sorbent loading. Thin cell walls are preferred to reduce energy requirements during desorption, as they heat a smaller mass of non-active components. Similarly, a thicker sorbent film can reduce energy needs by releasing more CO_2 during the same desorption process. However, manufacturing these structures poses challenges due to monolith stability and sorbent adhesion. An alternative approach involves using sorbents with higher equilibrium capacities, although the practical utility of equilibrium sorption capacity for assessing sorbents' use is limited. Additionally, fiber contactors are mentioned as another solution offering low-pressure drops for DAC applications, underscoring the shift toward more efficient contactor designs to improve DAC technologies' energy efficiency and feasibility.

Similarly, the IEA report highlights replacing high-pressure fans with low-pressure blowers and optimizing airflow patterns can significantly reduce fan energy use.[4]

Erans et al. specify the minimum energy requirement for DAC as approximately 1.8 GJ per ton of CO_2 for the capture process alone.[15] Additionally, compressing CO_2 to a supercritical state for transportation and storage requires about 0.11 GJ per ton. These figures highlight the significant energy demand of DAC technologies, underscoring the importance of utilizing energy-efficient methods and renewable energy sources to make DAC a viable and environmentally friendly option for carbon dioxide removal from the atmosphere.

Kung et al. mention that all known technologies face the challenge of high current energy requirements and cost (measured plant performance data: heat, 1500 kWh per tCO_2; electricity, 500 kWh per tCO_2; and cost, USD600–1000 per tCO_2).[16–19]

The sorbent material, which chemically binds to CO_2 molecules from the air, is at the core of DAC technology.[20–23] Once the sorbent material is saturated, it undergoes a regeneration phase. This regeneration is critical for the DAC process to be cyclical and sustainable. However, it is also a substantial energy user, requiring thermal energy to release the captured CO_2. The heating can be achieved through electrical means or by burning natural gas, contributing to the system's energy requirements. In solvent-based DAC systems, the regeneration step is energy intensive, involving releasing captured CO_2 from the solvent. This step typically requires significant thermal energy. The process often involves heating the solvent to break the chemical bonds that have trapped the CO_2, allowing it to be released and captured. The energy requirement for the regeneration phase in solvent-based DAC systems is substantial, particularly during the calcination process. The calciner, which decomposes $CaCO_3$ at high temperatures (around 900 °C), demands significant thermal energy. This requirement can be quantified as exceeding the enthalpy of decomposition of $CaCO_3$ at 900 °C, which is approximately 170 kJ/mol, translating to about 4.0 GJ/tCO_2. The energy requirements for sorbent regeneration in DAC systems vary substantially based on the sorbent type. For liquid sorbents, the regeneration process demands approximately 6 to 10 GJ of energy per ton of CO_2 captured. In contrast, solid sorbents are relatively more energy efficient, requiring only about 4 to 6 GJ per ton of CO_2 for regeneration. This difference highlights the inherent efficiency challenges and opportunities in optimizing DAC technology.[2]

Other sources sites that sorbent DAC currently needs 10–12 GJ/ton thermal while Carbon Engineering's process uses about 6 GJ/ton thermal energy.[16,17,24]

The paper by McQueen et al. explores the energy sources for solvent-based DAC, comparing natural gas versus electricity.[25] It assesses eight energy systems for a DAC process capturing 1 $MtCO_2$/year, requiring roughly 240 to 300 MW of steady power. The study finds the cost contribution of DAC's energy system varies significantly based on the source, with natural gas systems adding \$80/tCO_2 at \$3.25/GJ gas price. Leakage in the natural gas supply chain notably increases net capture costs. All electric systems' capture costs depend on electricity prices, with costs rising approximately \$2/tCO_2 for every \$/MWh increase in electricity cost. The analysis provides insights into the economic viability of different energy sources for DAC, highlighting the impact of energy costs and supply chain emissions on overall capture costs.[25] The specific energy requirements for this step can vary depending on the type of solvent used and the system's design, but it is generally one of the most energy-demanding parts of the DAC process. Studies estimate that solvent regeneration in amine-based DAC systems consumes 30–50% of the total energy consumption in a DAC plant.[4,26] This makes it the second largest energy user after fans, highlighting the need for optimization. The specific energy demand for solvent regeneration depends on several factors, including the chosen solvent material, regeneration temperature, pressure, and the efficiency of the regeneration process. Different regeneration strategies offer varying energy demands and efficiencies. There could be opportunities for significant optimization through (1) Exploring solvents with lower regeneration temperatures and higher CO_2 capacity, (2) Implementing advanced heat exchangers, waste heat utilization, and integration with renewable energy sources, (3) Investigating the potential of solid sorbents and other capture technologies with potentially lower regeneration energy requirements.

Various regeneration strategies can be applied to develop cost-effective and sustainable DAC technologies. This includes.[26]

Temperature swing adsorption (TSA)

Simple and established technology, but with the highest energy consumption due to high regeneration temperatures requiring significant heat input. Estimated energy demand: 400–900 kWh per ton of CO_2 captured.[27,28]

Pressure swing adsorption (PSA)

Lower energy demand than TSA, but limited CO_2 capture capacity. Lower energy consumption compared to TSA due to utilizing pressure swings instead of temperature. The estimated energy demand is 200–400 kWh per ton of CO_2 captured. However, PSA often has lower CO_2 capture capacity compared to TSA.[29] Recent research evaluating the energy dynamics of temperature swing versus pressure swing CO_2 separation processes, particularly for a generic adsorbent characterized by a heat of adsorption of − 65 kJ/mol, has revealed distinct operational efficiencies. The studies by Lackner and Lively and Realff indicate that TSA exhibits greater efficiency in scenarios involving dilute CO_2 concentrations, such as achieving 50% CO_2 removal from the feed and attaining 95% product purity.[30,31] This efficiency is attributed to TSA's effectiveness in selectively capturing CO_2 at low concentrations. In contrast, PSA demonstrates superior performance in bulk gas separation applications. The requirement to pressurize the inlet feed, especially when the CO_2 concentration is low, renders TSA less energy efficient compared to PSA for these specific separation tasks. This analysis underscores the need to match the CO_2 separation technology with the specific concentration conditions of the feed gas to optimize energy consumption.

Vacuum swing adsorption (VSA)

Lower energy consumption than TSA but requires complex vacuum pumps and limited CO_2 capture rates. The lowest energy consumption is due to vacuum swings, avoiding high temperatures and pressures. The estimated energy demand is 100–300 kWh per ton of CO_2 captured. However, VSA requires complex and expensive vacuum pumps and its CO_2 capture capacity can be even lower than PSA.[32,33]

Hybrid approaches

Combining different strategies for improved efficiency and adaptability. By combining lower energy-consuming strategies like PSA or VSA for specific stages, hybrid approaches can significantly reduce the overall energy consumption compared to pure TSA. Each stage can be optimized for its specific function, potentially leading to lower energy requirements than using a single technology for the entire process. Hybrid approaches can utilize heat generated in one stage for another, reducing overall energy consumption.[34,35]

A recent study by Madhu et al. presents a comprehensive lifecycle assessment (LCA) of various DAC technologies, offering crucial insights into their energy consumption and economic viability.[36] The authors meticulously compare two prevalent approaches: temperature swing adsorption (TSA) and high-temperature aqueous solution (HT-Aq). Their findings reveal a complex interplay between energy requirements and cost considerations, influencing the selection of optimal DAC strategies for specific project objectives.

The analysis demonstrates that TSA boasts superior energy efficiency, demanding only 0.7–1.3 kWh per ton of CO_2 captured (tCO_2), significantly lower than HT-Aq's 1.4–2.3 kWh/tCO_2. This disparity arises from the inherently energy-intensive regeneration process in HT-Aq. However, cost analysis presents a contrasting picture. While TSA exhibits a more favorable range of \$100–200/tCO_2, HT-Aq's price tag can reach a staggering \$250–500/tCO_2 due to expensive materials and complex operational demands.

Further complicating the selection process, are scalability challenges currently hindering TSA's wider deployment. Therefore, the optimal DAC technology hinges on project-specific priorities. If minimizing energy footprint holds paramount importance, TSA emerges as a promising candidate. Conversely, projects prioritizing immediate cost-effectiveness might lean toward HT-Aq despite its higher emissions.

Beyond the immediate findings, the study underscores the critical need for future research and development efforts. Both TSA and HT-Aq possess untapped potential for significant energy and cost reductions. Integration of renewable energy sources, improvement in capture and regeneration efficiencies, and economies of scale achieved through wider implementation could pave the way for a more sustainable and economically viable future for DAC technologies.

Following the capture and release of CO_2 from the sorbent, the gas is compressed for storage or utilization. Compression is necessary to reduce the volume of CO_2, making it manageable for transportation and storage. The compression step alone can consume hundreds to over a thousand kilowatt-hours per ton of CO_2, depending on the final pressure required.

The correlation between the final pressure of CO_2 compression and the estimated energy consumption required for the compression process in kilowatt-hours per ton of CO_2 (kWh/ton CO_2) varies. One can categorize the compression process into four pressure ranges: low (5–10 bar), medium (20–40 bar), high (40–100 bar), and very high (over 100 bar). The energy consumption increases with the pressure level; for low-pressure compression, the energy required is between 100 and 200 kWh/ton CO_2, whereas medium pressure requires 200–400 kWh/ton CO_2. High-pressure compression demands significantly more energy, between 400 and 800 kWh/ton CO_2. For very high-pressure scenarios, the energy consumption exceeds 800 kWh/ton CO_2, potentially reaching or surpassing 1000+ kWh/ton CO_2.[37–39]

This underscores the exponential increase in energy requirements as the desired pressure level for CO_2 storage or utilization escalates, illustrating a key consideration for the design and operation of CO_2 capture and sequestration systems.

Factors influencing this demand include the employed compressor type and its efficiency, operating temperatures, and integration with renewable energy sources. While high pressures necessitate the most significant energy input, meticulous process optimization and leveraging renewable power offer promising avenues for mitigating the environmental and economic burden of CO_2 compression. Therefore, selecting the optimal compression strategy ensures DAC technology's overall efficiency and sustainability.

Overall, the total energy required for a DAC system is a cumulative result of these individual processes. The system's size, the efficiency of the sorbent materials, and the specific design and technology used all influence the total energy consumption. Contemporary assessments indicate that DAC systems necessitate an energy input ranging from 2000 to 3000 kWh to sequester one metric ton of CO_2. This range of energy consumption is delineated in studies referenced at [2] and [3]. This estimation encompasses the cumulative energy requirements across various operational components of DAC systems. Notably, it includes the energy utilized by fans for facilitating air movement through the DAC system, which is critical for ensuring adequate contact between air and the sorbent material.

Additionally, a significant portion of this energy estimate is allocated to the thermal energy required to regenerate the sorbent material. This process is essential for the continuous operation of DAC systems, as it allows for the release and subsequent capture of CO_2 from the sorbent material. The regeneration phase typically involves the application of heat to break the bonds between the sorbent and the adsorbed CO_2, thereby enabling the reusability of the sorbent.

Furthermore, the electrical energy necessary to compress the captured CO_2 step is vital for facilitating the storage or utilization of CO_2 in various applications, such as synthetic fuel production, enhanced oil recovery, or permanent sequestration. Compression is an energy-intensive process, given the need to convert the gaseous CO_2 into a supercritical or liquid state, which requires maintaining high pressure and, in some cases, lower temperatures.

The cited energy range for capturing one ton of CO_2 in DAC systems thus reflects a comprehensive accounting of the primary energy-consuming processes involved in the technology. It underscores the importance of energy efficiency in the design and operation of DAC systems, particularly in their scalability and integration into broader carbon management strategies.

The energy-intensive nature of each step in the DAC process highlights the importance of optimizing each phase to minimize total energy consumption. Innovations in material science for more efficient sorbents, advancements in system design for better heat integration, and the utilization of renewable energy sources to power these processes are crucial areas of development. As the DAC industry progresses, reducing the energy requirements of each step will be pivotal to improving the overall carbon footprint and economic viability of DAC as a tool for combatting global CO_2 levels.

Two main processing steps that require heat

DAC technologies are emerging as a vital component in reducing atmospheric CO_2 levels in carbon capture. The DAC process is particularly heat intensive, involving two primary stages that necessitate thermal energy to facilitate CO_2 processing. Details of liquid and solid sorbent carbon capture, including both absorption and adsorption processes, have been comprehensively explained in previous publications.[2,20]

One of the stages in the process is sorbent regeneration in solid DAC. After the sorbent material has chemically bound CO_2 from the air, it must be regenerated–that is, it needs to be cleared of the captured CO_2 to regain its absorbing capacity. This regeneration is achieved by applying heat, which detaches the CO_2 molecules from the sorbent. The required temperature for this process varies with the sorbent's chemical makeup, typically ranging from a moderate 80 °C to a high of 900 °C. The considerable span in temperature reflects the diversity of sorbent materials employed in various DAC systems and underscores the tailored approach needed for different chemical compositions.[2]

Another critical step involves CO_2 desorption from liquid solvents, which is applicable in DAC systems that utilize liquid-based capture methods. In these systems, the solvent that has absorbed CO_2 must be heated to a point where the CO_2 is released in a concentrated form suitable for storage or subsequent use. This energy-intensive desorption step is a key determinant of the DAC system's overall operational efficiency.[2]

Both sorbent regeneration and CO_2 desorption are energy-intensive processes that contribute to the total energy footprint of DAC operations. The energy requirements for sorbent regeneration and CO_2 desorption in DAC systems vary significantly based on the type of sorbent and desorption method used. For liquid solvents, the sorbent regeneration process typically demands between 6 and 10 gigajoules (GJ) per ton of CO_2. This is comparatively higher than solid sorbents, which require between 4 and 6 GJ per ton of CO_2 for regeneration. The desorption of CO_2, a critical step in the DAC process, also exhibits variability in energy consumption. When direct heat is applied for CO_2 desorption, the energy requirement ranges from 2 to 5 GJ per ton of CO_2. In contrast, indirect heat pumps for CO_2 desorption are more energy efficient, necessitating only 1 to 3 GJ per ton of CO_2. These figures underscore the substantial energy input required for both sorbent regeneration and CO_2 desorption, highlighting the need for efficient technologies and processes in the DAC system to minimize the overall energy footprint.[40,41]

The efficiency with which these heat-dependent steps are managed significantly influences the practicality and sustainability of DAC as a carbon mitigation strategy. Consequently, ongoing research and development focus on optimizing these thermal processes, seeking to lower-temperature requirements and enhance energy efficiency. This optimization is paramount for DAC to become a scalable and economically feasible solutions in the global effort to reduce greenhouse gas concentrations in the atmosphere.[42]

In the context of DAC systems, the provision of heat is a pivotal component, often satisfied by various external sources. Natural gas burners, for instance, are a standard solution, offering a reliable and controlled heat supply. These burners combust natural gas to generate the high temperatures needed for sorbent regeneration, where CO_2 is released from the capturing medium. However, their use presents a paradox, as the combustion process emits CO_2, potentially offsetting the benefits of the DAC system unless the emissions are captured or offset.

Another widely used heat source is steam, which can be generated from various energy inputs, including fossil fuels, biomass, or excess heat from power generation. Steam provides a versatile medium for transferring heat and can be integrated into DAC systems to facilitate the desorption of CO_2 from liquid solvents. This method is particularly beneficial for utilizing waste steam from industrial processes, thereby enhancing energy efficiency.

Steam offers several advantages for DAC systems: (1) Versatility: steam can be easily controlled and adjusted to provide the required heat for solvent desorption at different temperatures. (2) Integration: Existing steam infrastructure in many industries can be leveraged for DAC, reducing capital costs and facilitating integration. (3) Waste heat utilization: Utilizing waste heat from industrial processes or power plants can significantly reduce the energy footprint of DAC, boosting its sustainability.[4] The Climeworks Orca plant in Iceland's commercial DAC plant uses geothermal energy to generate steam for solvent regeneration, showcasing the potential for clean and renewable heat sources.

Industrial waste heat represents a resourceful and sustainable approach to supplying the necessary thermal energy for DAC systems. This form of heat is a byproduct of numerous industrial processes and typically goes unused. DAC operations can significantly reduce energy costs and improve their carbon footprint by harnessing this waste heat. Utilizing waste heat recovers energy that would otherwise be lost and aligns with circular economy principles, contributing to broader sustainability goals.

Harnessing industrial waste heat offers a promising and sustainable approach to powering DAC systems. Global waste heat availability is estimated to be around 5 EJ (exajoules) per year, sufficient to power a significant portion of future DAC deployment. Industries like steel, cement, chemicals, and refineries generate substantial waste heat at temperatures suitable for DAC solvent regeneration (80–130 °C).[43,44] In Europe, an estimated 15–20% of industrial energy demand could be met through waste heat utilization, including potential applications in DAC.[45]

Benefits for DAC include (1) Reduced energy costs: Utilizing waste heat eliminates the need for additional energy generation, potentially leading to significant cost savings compared to conventional heat sources; (2) Improved carbon footprint: Replacing fossil fuel-based heat with waste heat can drastically reduce the carbon footprint of DAC operations, promoting broader sustainability goals; and (3) Enhanced energy efficiency: Waste heat utilization aligns with principles of circular economy and resource recovery, maximizing energy efficiency and minimizing environmental impact.

These external heat sources play a critical role in the functionality and efficacy of DAC systems. The choice of heat source has profound implications for the carbon capture process's operational costs, energy efficiency, and overall environmental impact. As the global community continues to seek solutions for reducing atmospheric carbon levels, optimizing and selecting heat sources for DAC will remain a subject of significant importance and ongoing innovation.

A cheaper heat source is required for the regeneration process: Natural gas?

The quest for cost-effective and efficient DAC of CO_2 is leading to pivotal discussions around the heat sources required for the sorbent regeneration process. A prominent candidate is natural gas due to its widespread availability and high energy content. When combusted, natural gas (NG) yields approximately 5000 kilowatt-hours (kWh) of thermal energy per ton of CO_2 emitted, presenting a substantial heat output that can be harnessed for DAC operations.[46] Intriguingly, the energy requirement for DAC systems to capture and remove a ton of CO_2 is significantly lower, estimated at only 2200 kWh. This differential suggests that, despite the emissions from natural gas combustion, the process results in a net reduction of CO_2 in the atmosphere when integrated with DAC technology.

However, using natural gas as a heat source brings forth a paradox. While it may offer a cheaper and readily available option for the regeneration heat required in DAC systems, it also contributes to greenhouse gas emissions, which DAC seeks to mitigate. The balance, therefore, tilts favorably when considering the overall carbon equation–more CO_2 is removed from the atmosphere by the DAC process than is emitted by burning the natural gas. This net removal is a compelling argument for using natural gas as a transitional heat source in DAC systems, mainly when renewable sources are not feasible or available.

In the context of journal discussions, the natural gas proposition underscores a pragmatic approach to advancing DAC technology. It highlights a viable pathway for enhancing the affordability and scalability of DAC operations in the near term, while the search for zero-emission heat sources continues. As the technology and infrastructure for renewables advance, such non-renewable sources are expected to be phased out. Until then, the focus remains on optimizing the balance between operational feasibility and environmental stewardship within the DAC domain.

In evaluating the viability of using NG to provide thermal energy for DAC processes, it is crucial to consider the full lifecycle emissions of NG, including extraction and transportation. These emissions can significantly affect the overall carbon footprint of DAC operations. Additionally, the energy required for DAC is substantial and may approach the amount contained in the fuels originally producing the CO_2. Notably, these energy estimates typically do not account for additional energy inputs needed for CO_2 transport and storage, which can be considerable depending on the method and location of storage. Therefore, while NG may serve as a transitional energy source, its effectiveness and sustainability must be critically assessed in light of these factors.[47,48]

Comparative energy requirements for liquid and solid DAC technologies

In comparing the energy requirements of liquid and solid DAC technologies, liquid sorbents typically demand more energy, especially in the sorbent regeneration phase due to high-temperature requirements. On the other hand, solid sorbents generally require less energy for regeneration, as they can operate effectively at lower temperatures. This results in a more energy-efficient process overall. However, the specific energy requirements can vary based on the type of sorbent used and the design of the DAC system.

Figure 1 delineates the energy requirements for solid and liquid DAC technologies, comparing their reliance on heat and electricity as energy inputs. Solid DAC systems, when paired with heat, demand a moderate amount of energy, with the low and high estimates ranging between 2.9 and 5.5 gigajoules per ton of CO_2 (GJ/t CO_2). However, when electricity is used, the energy requirement for solid DAC significantly diminishes, with estimates between a mere 0.6 and 1.1 GJ/t CO_2, showcasing a substantial efficiency gain.[2]

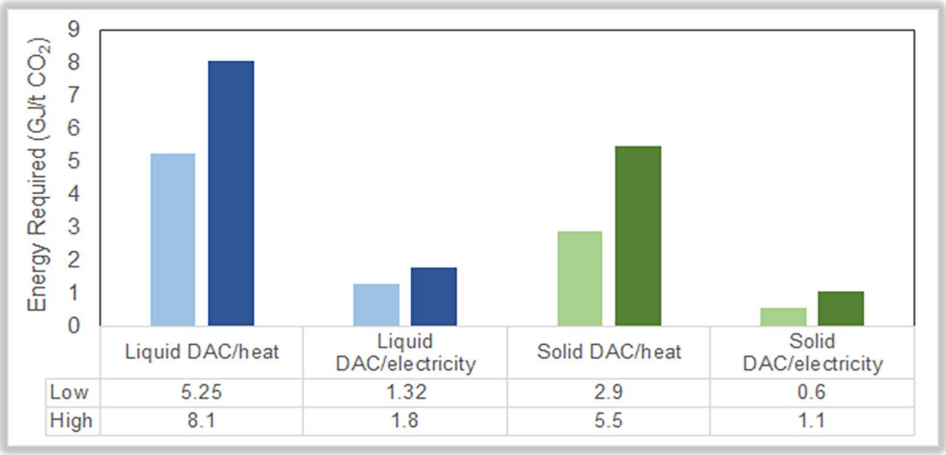
Conversely, liquid DAC technologies show a stark contrast in their energy consumption. When utilizing heat, the energy required spikes to a range of 5.25 to 8.1 GJ/t CO_2, indicating a higher energy intensity compared to its solid counterpart. The liquid systems that use electricity also follow this trend, but the energy required drops to 1.32 and 1.8 GJ/t CO_2, which is higher than solid DAC with electricity but more efficient than liquid DAC with heat.[2]

The comparative analysis suggests that solid DAC systems, especially those utilizing electricity, offer a more energy-efficient solution for carbon capture. This stark contrast in energy requirements emphasizes the critical role of the energy source in determining the environmental and economic feasibility of DAC technologies. With energy efficiency being a paramount consideration in carbon capture processes, solid DAC with electricity stands out as a potential leader for sustainable carbon capture solutions.

This graphical representation underscores the variability in energy demands across different DAC technologies, highlighting the importance of considering energy input types in evaluating and optimizing carbon capture solutions. The clear visual contrast between the technologies suggests that solid DAC using electricity may offer a more energy-efficient solution for CO_2 capture, which is crucial for the overall sustainability of the carbon capture process.

Comparison of operational mechanisms and implications for the liquid and solid DAC technologies

Details of liquid and solid sorbent carbon capture, including both absorption and adsorption processes, have been comprehensively explained in previous publications.[2,20] Table 1 contrasts Liquid and Solid Sorbent DAC technologies, focusing



	Liquid DAC/heat	Liquid DAC/electricity	Solid DAC/heat	Solid DAC/electricity
Low	5.25	1.32	2.9	0.6
High	8.1	1.8	5.5	1.1

Figure 1. Comparative Energy Requirements for Liquid and Solid DAC Technologies. The chart displays two bars for each technology type, representing the 'Low' and 'High' energy consumption estimates. The energy required for the Liquid DAC/heat method ranges from a low of 5.25 GJ/t CO_2 to a high of 8.1 GJ/t CO_2. In contrast, the Liquid DAC/electricity shows a more energy-efficient profile, requiring only 1.32 GJ/t CO_2 at the low end and 1.8 GJ/t CO_2 at the high end. The chart shows that both the heat and electricity requirements for solid DAC are noticeably less than the Liquid DAC[2,3].

Table 1. Comparative analysis of liquid versus solid sorbent direct air capture technologies: operational mechanisms and implications.

Aspect	Liquid sorbent DAC	Solid sorbent DAC
Mechanism	Utilizes aqueous amine solutions for CO_2 absorption through chemical interaction	Employs amine-functionalized porous materials for physical CO_2 adsorption
Energy Consumption	High thermal energy input for solvent regeneration at elevated temperatures	Lower thermal energy input due to reduced temperatures for regeneration
Efficiency	Dependent on the chemical properties and reaction kinetics of solvents	Determined by surface area, porosity, and chemical bond strength of materials
Operational Considerations	Complex management with significant water and energy use	More straightforward, with increased durability and less susceptibility to material degradation
Environmental Impact	Risk of solvent leakage and associated environmental concerns	Lower environmental risk due to the absence of liquid contaminants and reduced water usage
Scalability	Scaling up presents challenges due to the need for complex system management	Potential for modular scalability, albeit with its own set of challenges
Cost	High costs associated with solvent technology development and system implementation	Initial high costs with ongoing research aimed at cost reduction through material innovation
Research and Development Stage	Well established, with research focused on improving solvent efficiency	Less mature but rapidly evolving, with significant potential for material advancements

on their mechanisms, energy consumption, and operational aspects. Comparing liquid and solid sorbent DAC technologies, liquid sorbents, typically amine based, chemically absorb CO_2 but require high thermal energy for regeneration, posing spillage and secondary pollution risks. Solid sorbents, using materials like zeolites, physically adsorb CO_2 at lower energy costs and with fewer environmental risks. Liquid systems offer high efficiency but are operationally complex and costly. Solid systems, while simpler and potentially more durable, are in a less mature development stage. Both face scalability challenges, yet solid sorbents present a more environmentally friendly option with ongoing advancements expected to lower costs. Both are costly, but research is active in enhancing solvent efficiency and material innovation for solid sorbents. Ozkan et al. bring together perspectives from various thought leaders on the scalability of DAC technology.[42] The consensus is that while DAC is a promising technology for removing CO_2 from the atmosphere and combating climate change, it faces significant challenges. These include the high energy demands for sorbent material regeneration and the need for large-scale infrastructure. Some experts highlight the current success of commercial operations and the potential for billion-ton scale removal by 2050, while others point out the efficiency and economic challenges compared to other carbon mitigation methods. The discussion also covers the importance of policy frameworks, renewable energy integration, and DAC's role in offsetting hard-to-avoid emissions.

Recent advancements in liquid and solid sorbents for carbon capture have shown promising results. Pioneering developments in liquid sorbents, particularly aqueous amino acids, have been explored for their potential in carbon capture. These sorbents are environmentally benign and can be regenerated with relatively low heating, around 100 °C. An amino acid-based sorbent with a notable capacity of 0.7 mol of CO_2 per mol of aqueous solution under ambient air conditions. They innovatively utilized a 2,6-pyridine-bis(iminonoguanidine) (PyBIG) compound to crystallize CO_2-saturated bicarbonate species into a solid hydrated carbonate within the solution.[49]

Furthermore, other research teams have made significant strides with aprotic heterocyclic anion (AHA) ionic liquids (ILs) for CO_2 capture. These ILs maintain a constant viscosity pre- and post-CO_2 absorption, supporting efficient CO_2 sorption with a 1:1 stoichiometry. Additionally, these ILs exhibit a lower reaction enthalpy of approximately 50 kJ/mol compared to conventional amines, allowing for regeneration at temperatures below 100 °C while still offering substantial working capacity.[50]

This lower enthalpy is a key advantage, reducing the energy requirements for sorbent regeneration and making AHA ILs a promising avenue in carbon capture technology.

In emerging solid sorbents for carbon capture, significant advancements have been made in enhancing CO_2 absorption capacities at low CO_2 partial pressures. An ethylene diamine (ED)-modified ED-Mg/DOBDC sorbent demonstrated a remarkable CO_2 capture capacity of 1.5 mmol/g under ambient conditions. This capacity is complemented by excellent thermal stability and regenerability. The innovation lies in introducing amine groups grafted onto the open metal sites of the metal–organic framework (MOF), thereby providing additional chemisorption sites and enhancing the CO_2 capacity beyond that of the parent MOF (1.35 mmol/g).[51]

Similarly, alkylamine-loaded Mg2(dobpdc) with a CO_2 uptake capacity of 2 mmol/g under a CO_2 partial pressure of 390 ppm at 25 °C is achieved.[52]

The enhanced CO_2 uptake at low partial pressure is attributed to the interaction between the electrophilic carbon of CO_2 and the electron pair on the nitrogen in diamine. Further, modified MOFs are used to increase their CO_2 capture efficiency. By incorporating amine molecules into the pores of a simple MOF, specifically MIL-101(Cr), they achieved a significantly higher CO_2 capacity. The tris(2-amino ethyl) (TREN)-loaded MIL-101(Cr) demonstrated an eightfold increase in CO_2 capacity (2.8 mmol/g) compared to the unmodified MOF (0.35 mmol/g) at a CO_2 partial pressure of 0.4 mbar (400 ppm CO_2 in He) and a temperature of 25 °C.[53] This underscores the effectiveness of functionalizing MOFs with amines to boost their CO_2 absorption capabilities.

The field of DAC is poised for significant advancements through the development of structure–property–performance relationships in sorbent materials. Fundamental research is crucial to deepen our understanding of these correlations, which will, in turn, facilitate the optimization and widespread application of sorbents in DAC technologies. Furthermore, integrating computational studies, particularly leveraging advanced techniques, such as machine learning, is essential. These computational approaches can significantly expedite the discovery and development of new sorbents, enabling rapid screening and prediction of material performance. Combining fundamental studies with cutting-edge computational methods, this integrated approach is pivotal in advancing the effectiveness and efficiency of sorbents for DAC and driving the technology toward broader applicability in addressing climate change challenges.

COST analysis of renewable energy sources for direct air capture

Conducting a cost analysis of renewable energy sources for DAC involves assessing the capital and operational expenditures associated with various renewable options like solar, wind, and geothermal energy. It is crucial to analyze the efficiency, reliability, and availability of these energy sources, as well as the compatibility with DAC technology. The analysis must account for the intermittent nature of some renewables, the need for energy storage, and potential grid integration costs. The aim is to identify the most economically viable renewable energy solutions that can sustainably power DAC systems while minimizing the carbon footprint.

The bar chart in Fig. 2 presents the cost variability associated with powering DAC technology using different energy sources. It compares the low and high-cost estimates for capturing one ton of carbon using solar with storage, nuclear, wind with storage,

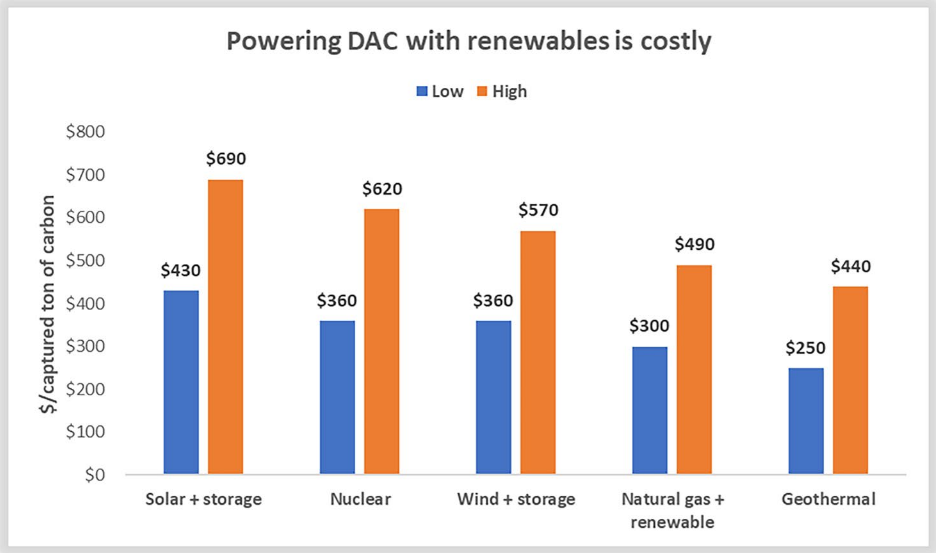


Figure 2. Cost Analysis of Renewable Energy Sources for DAC. This bar chart displays the cost of carbon captured per ton at low and high-cost estimates for various renewable energy sources powering DAC systems. The comparison includes solar with storage, nuclear, wind with storage, natural gas & renewable hybrid, and geothermal energy. The data indicate the economic challenge of utilizing renewable energy for DAC, with solar + storage having the highest cost variance and geothermal having the lowest cost to power DAC plants[2,3].

natural gas with renewable hybrid systems, and geothermal energy. The data show that solar with storage has the widest cost range, from 430 to 690 dollars per ton of carbon. This reflects the variability in solar energy availability and the costs associated with energy storage systems.[2,22,54]

Nuclear energy presents a somewhat narrower cost range, from 360 to 620 dollars per ton, suggesting it may offer a more stable but still variable cost option for DAC. Wind with storage shows a slightly lower cost range than nuclear, from 300 to 570 dollars per ton. This may indicate the growing efficiency and decreasing costs of wind energy technology and storage solutions.

The natural gas and renewable hybrid option display costs ranging from 250 to 490 dollars per ton, which could indicate the benefits of combining intermittent renewable sources with the reliability of natural gas. However, it is important to consider the potential greenhouse gas emissions associated with natural gas usage.

Lastly, geothermal energy is presented as the least variable and potentially the most cost-effective option, with a cost range from 250 to 440 dollars per ton. This might reflect the consistent availability and established technology of geothermal energy, which can provide a steady energy supply for DAC without extensive storage solutions.

The chart conveys a clear message: the cost-effectiveness of DAC varies notably depending on the renewable energy source used. Solar with storage can be the most costly, while geothermal presents as a more cost-consistent option. This visualization underscores the importance of energy source selection in carbon capture technologies' financial feasibility and environmental impact. Such data is crucial for policymakers and investors when considering integrating DAC systems into broader climate mitigation strategies. The analysis indicates that while renewable energies are a sustainable choice for powering DAC, their economic viability must be carefully evaluated to optimize environmental and financial outcomes.[2]

The data presented elucidate a crucial aspect of DAC technologies–the economic feasibility of renewable energy sources is as significant as their environmental benefits. While solar energy with storage might capture the highest percentage of carbon per ton, its cost variability indicates that it may not always be the most economical option. Conversely, geothermal energy is more consistent and potentially cost-effective for DAC operations.

The paper by Sabatino et al. provides a comparative analysis of DAC technologies, focusing on energy consumption and reactor scenarios among three main DAC processes: alkali scrubbing, amine scrubbing and solid sorbent processes.[55] It evaluates these technologies based on their productivity, exergy and energy consumption through process simulations and mathematical optimization. The study highlights the potential of solid sorbent-based processes to offer better performance due to their lower exergy demand and suggests that all technologies could potentially operate below \$200/ton CO_2 under realistic energy and reactor costs. The detailed analysis seeks to optimize DAC technologies for large-scale deployment, emphasizing the critical role of capital cost and the influence of mass transfer efficiency on the economic feasibility of DAC solutions.

Aspects of energy and heat demand, efficiency, flexibility, and cost impact

DAC technology, a critical component in the arsenal against climate change, harnesses unique methods to extract CO_2 directly from the atmosphere. Among these, Liquid Sorbent DAC and Solid Sorbent DAC emerge as two distinct approaches, each with its operational characteristics and implications for energy use, efficiency, and environmental impact. Liquid Sorbent DAC is known for its high energy requirements, relying on substantial amounts of electricity and heat, and operating at elevated temperatures that often necessitate external heat sources. This operational paradigm, while effective, leads to lower energy efficiency and poses challenges in terms of cost and sustainability.

Table 2. The comparison of two types of DAC technologies: Liquid sorbent DAC and solid sorbent DAC, across various aspects of energy and heat demand, efficiency, flexibility, and cost impact.

Aspect	Liquid sorbent DAC	Solid sorbent DAC
Energy Demand	High; both electricity and significant heat required	Lower compared to liquid; mainly electricity for operations
Heat Demand—Temperature	High temperature (typically 900 °C)	Lower temperature (generally below 100 °C)
Heat Demand—Source	External sources like natural gas burners, steam, or industrial waste heat	Possibility of using low-grade heat, such as waste heat or solar thermal energy
Energy Efficiency	Lower due to high heat requirements	Higher due to lower heat requirements
Flexibility in Heat Source	Less flexible due to high-temperature requirements	More flexible with lower-temperature requirements
Impact on cost and Feasibility	The major factor in overall cost and high demand impacts sustainability	Lower energy and heat demands reduce operational costs and improve the environmental profile

Conversely, Solid Sorbent DAC represents a more energy-conservative option, functioning at significantly lower temperatures and predominantly utilizing electricity, which opens doors to integrating more sustainable heat sources. This contrast in operational dynamics between the two systems highlights a crucial aspect of DAC technology: the careful balance between efficacy in CO_2 capture and the practicality of implementation, both in economic and environmental terms. Table 2 depicts comparison between the liquid and solid sorbent DAC technologies.

Liquid Sorbent DAC is characterized by high energy demand, requiring both significant electricity and heat. It operates at high temperatures, typically around 900 °C and often relies on external heat sources like natural gas burners, steam, or industrial waste heat.[2]

However, this technology has lower energy efficiency due to its high heat requirements and less flexibility in heat sources due to the need for high temperatures. Consequently, the cost and feasibility are heavily impacted; the high energy demand is a major factor in the overall cost, affecting the sustainability and economic viability of the technology.

On the other hand, Solid Sorbent DAC has a lower energy demand, primarily using electricity for its operations. It functions at lower temperatures, usually below 100 °C, allowing for the use of low-grade heat sources, such as waste heat or solar thermal energy.[2]

This results in higher energy efficiency and more flexibility in heat source choice due to the lower-temperature requirements. The significant outcome of these attributes is a lower impact on operational costs and an improved environmental profile, enhancing the feasibility of solid sorbent DAC as a carbon capture solution.

In the evolving landscape of DAC technologies, the efficiency and sustainability of different approaches are under constant scrutiny. Solid sorbent DAC systems are emerging as promising solutions due to their superior energy and heat efficiency. This efficiency contributes to long-term cost savings and substantially reduces the environmental impact of the carbon capture process. The lower energy requirements of these systems result in decreased operational costs and a diminished carbon footprint, making them a more sustainable option in the quest to mitigate climate change.

A notable advantage of solid sorbent DAC lies in its operational flexibility. This technology can effectively utilize low-grade heat sources, such as waste heat or solar thermal energy. This flexibility allows for easier adaptation to diverse environmental conditions and operational settings, enhancing the feasibility and scalability of solid sorbent DAC systems in different contexts. Such adaptability is crucial for integrating DAC technology into existing industrial and energy landscapes.

The cost-effectiveness of solid sorbent DAC systems is another significant benefit. Owing to their lower energy demands and the potential for integrating waste heat, these systems can provide a more economically viable solution for carbon capture. This affordability is a key factor that makes solid sorbent DAC an attractive option for large-scale implementation in various carbon capture initiatives.

Moreover, the shift toward solid sorbent-based DAC systems aligns closely with broader environmental conservation goals and reducing the carbon footprint. By optimizing the use of resources and minimizing emissions associated with the capture process, solid sorbent DAC contributes to the overall sustainability of the technology.

In contrast, liquid sorbent DAC systems, while effective in specific scenarios where high-temperature heat sources are readily available, may not offer the same level of versatility and sustainability as their solid counterparts. The comparative analysis of these technologies highlights a clear preference for solid sorbent DAC regarding versatility, sustainability, and cost-effectiveness. However, this does not diminish the potential application of liquid sorbent DAC in specific contexts where it may be more suitable.

This dichotomy between the two approaches underscores the need for ongoing research and development in DAC technologies. Enhancing the efficiency and integration of DAC systems into the broader energy system remains a priority. As advancements continue, it is expected that both liquid and solid sorbent DAC technologies will evolve, offering more refined solutions for carbon capture and contributing significantly to global efforts to combat climate change.

AN optimistic projection of the declining costs associated with DAC

Advancements in material science, process efficiencies, and economies of scale drive the projected decline in costs associated with DAC technology. As the technology matures and more facilities are deployed, operational and capital expenses are anticipated to decrease. This trend mirrors the cost trajectory observed in renewable energy sectors like solar and wind. Additionally, increased investment and research in DAC will likely spur innovations that further reduce costs, making it a more economically viable solution for large-scale carbon dioxide removal from the atmosphere.

Figure 3 presents an optimistic projection of the declining costs associated with DAC of CO_2 over time, highlighting technological advancements and economies of scale as the industry matures. In 2023, the cost to remove and store a ton of CO_2 ranges from $600 to $1,000. This figure includes the full end-to-end capturing and sequestering of atmospheric CO_2. By the end of the decade, the cost is anticipated to decrease significantly to $250–$300 per metric ton of CO_2 equivalent (mt CO_2e), with this cost reduction being attributed to the development of facilities capable of capturing multiple megatons of CO_2 annually.

End-to-end cost

Full lifecycle consideration Including end-to-end costs means that all stages of the DAC process are accounted for. This encompasses not only the energy and materials needed to capture CO_2

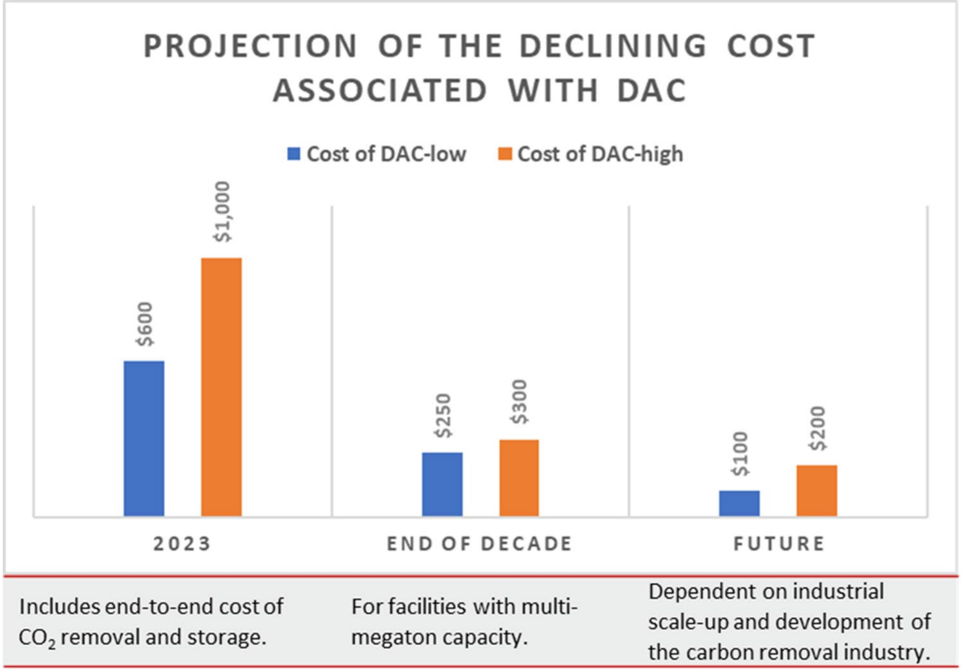


Figure 3. Projection of the declining cost associated with DAC. This bar graph illustrates the projected decrease in costs associated with DAC technology over three distinct timeframes: 2023, the end of the decade and a future scenario beyond that period. The graph compares two scenarios, denoted as DAC-low and DAC-high, which likely represent optimistic and conservative estimates, respectively. The initial costs in 2023 are substantially higher, with the conservative estimate at $1,000 per unit and the optimistic estimate at $500. As we approach the end of the decade, the costs are projected to halve, with the conservative estimate at $300 and the optimistic at $250. Looking into the future, the costs are anticipated to reduce further to $200 for both estimates. This trend reflects the anticipated efficiencies gained from industrial scale-up and the development of the carbon removal industry, as well as potential advancements in DAC technologies and infrastructure, particularly in facilities with multi-megaton capacity. The costs include the end-to-end process of CO_2 removal and storage.

from the atmosphere but also the costs associated with the purification, compression, transportation, and long-term storage of the captured CO_2. End-to-end costing ensures a more comprehensive view of the financial viability of DAC technology.

Technological integration The integration of various technological processes within DAC can lead to higher initial costs but might offer cost savings in the long run due to increased efficiency. For instance, coupling DAC with renewable energy sources could lead to a reduction in operating costs over time.

Storage costs Long-term storage of CO_2, whether in geological formations or through mineralization, must be safe and permanent. The costs include site selection, preparation, monitoring, and potential liabilities associated with leakage or other environmental impacts.

Facility capacity

Economies of scale The assumption here is that as DAC facilities grow in capacity, reaching multi-megaton scales, the average cost per ton of CO_2 captured will decrease. This is due to the distributed fixed costs over a larger quantity of captured CO_2, more efficient use of infrastructure, and potential bulk purchasing of materials and energy.

Operational efficiency Larger facilities may benefit from operational efficiencies, such as continuous operation (reducing downtime and maintenance costs per unit of CO_2 captured) and the use of more advanced and efficient capture materials and energy recovery systems.

Learning curve As more facilities are built and operated, there is typically a learning curve that leads to cost reductions. This includes improvements in construction practices, better process optimizations, and reductions in the cost of materials and equipment as suppliers also scale up production.

Industry growth

Technological advancements Future cost predictions assume significant technological advancements. This could mean breakthroughs in materials science leading to more effective and cheaper sorbents, improvements in process engineering, or innovations in energy recovery and utilization.

Increased investment For costs to decline, substantial investment is needed not only in the DAC facilities themselves but also in the research and development of new technologies. This investment could come from both public and private sources, driven by policy incentives or market demand for carbon removal.

Policy support Government policies can accelerate industry growth through subsidies, tax incentives, or carbon pricing mechanisms that make DAC more economically attractive. Furthermore, policies may also support the development of necessary infrastructure for CO_2 transport and storage.

Market development The creation of markets for captured CO_2, such as its use in synthetic fuels, materials, or enhanced oil recovery, can provide revenue streams that offset the costs of capture and storage, further driving down the end-to-end costs.

These assumptions rely on a complex interplay of technological, economic, and regulatory factors that will influence the cost trajectory of DAC. They are inherently optimistic, assuming a favorable alignment of these factors to achieve the projected cost declines.

Future directions

The imperative of integrating renewable energy sources into carbon capture technologies is not merely an environmental prerogative but a multifaceted strategy crucial for attaining sustainable development goals. The transition toward renewables in DAC systems demands not only an economic and operational synergy but also a forward-thinking approach that anticipates technological evolution and policy shifts.

Policymakers and stakeholders, deeply vested in renewable energy and climate change abatement, must engage in a profound, analytical exploration of the diverse economic landscapes shaped by these renewable alternatives. Investment strategies in DAC should be calibrated to enhance carbon sequestration efficiency while buffering against economic uncertainties' vicissitudes.[5,42] To promote long-term success in climate change initiatives, a comprehensive set of recommendations and analytical insights is presented:

Enhanced integration of renewable energy for sustainable DAC systems

The imperative for the strategic integration of renewable energy into DAC operations transcends environmental considerations and taps into the essence of sustainability. A comprehensive economic assessment of DAC is paramount, particularly those powered by intermittent renewable sources, such as solar and wind. This should entail a thorough investigation into cutting-edge energy storage technologies that can mitigate the fluctuations inherent to renewable sources. The conceptualization of hybrid systems that draw from a spectrum of renewable energies may hold the key to an economically and ecologically balanced synthesis.

Advancements in material science and process engineering for DAC

The frontier of DAC technology is defined by the evolution of material science and process engineering. The pursuit of novel sorbent materials that are low in energy demand, the refinement of carbon capture processes, and the minimization of auxiliary energy inputs are all areas ripe for innovation. Such advancements are the linchpins in reducing operational costs and amplifying system efficiency.

Conducive policy and regulatory frameworks

The scaffolding for the widespread adoption of efficient renewable energy in DAC systems is a robust policy and regulatory edifice. Policies incentivizing renewable integration, such as carbon credits, subsidies for green initiatives, and advantageous tariffs, could catalyze investments in superior DAC technologies.

Circular economy in DAC technology

Embracing the principles of the circular economy within DAC technology applications is paramount. This necessitates the reduction of waste, the development of regenerative CO_2 processes, and the valorization of captured carbon. This circularity is pivotal for climate mitigation and the economic resilience of carbon capture strategies. Furthermore, DAC technology enhances the circularity of carbon by not only reducing the concentration of atmospheric CO_2 but also providing a source of carbon for sustainable fuel production, carbon-neutral materials, and enhanced oil recovery processes.[56]

Balancing economic and sustainable outcomes in renewable energy for DAC

The discourse surrounding renewable energy's role in DAC underscores the need for a balanced approach that judiciously considers economic impacts alongside sustainability targets. A comprehensive assessment of renewable energy's economic implications is vital for stakeholders, including policymakers. Investments should be strategically channeled to enhance carbon capture efficacy while safeguarding against economic fluctuations, ensuring a sustainable trajectory for DAC technology.

The electrochemical reduction of CO_2

A visionary approach in carbon capture, the Electrochemical Reduction of CO_2 (ERC), represents a paradigm shift, transforming CO_2 into valuable byproducts such as CO, formic acid (HCOOH), and methane (CH_4) using electrical energy. ERC's capacity to customize production by modulating the electrochemical cell's voltage is a groundbreaking feature that simplifies the conversion process. This innovative method diverges from conventional DAC by obviating the need for thermal sorbent regeneration or gas pressurization, achieving notable energy savings and reducing greenhouse gas emissions.[57]

This article serves as a guidepost for emerging research and the development of actionable strategies that will shape the future of DAC and its role in our collective quest for a carbon-neutral society.

Declarations

Conflict of interest

The author declares no competing interests.

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REFERENCES

1. (IEA), I.E.A. (2022). Executive Summary—Direct Air Capture 2022—Analysis. https://www.iea.org/reports/direct-air-capture-2022/executive-summary. Accessed 29 April 2024
2. Ozkan, M., Nayak, S.P., Ruiz, A.D., and Jiang, W. (2022). Current Status and Pillars of Direct Air Capture Technologies. Iscience.
3. M. Ozkan, Direct air capture of CO2: A response to meet the global climate targets. MRS Energy Sustai. **8**, 51–56 (2021)
4. IEA (2022). Direct Air Capture 2022: A key technology for net zero. https://www.iea.org/reports/direct-air-capture-2022. Accessed 29 April 2024.
5. M. Ozkan, M. Atwood, C. Letourneau, C. Beuttler, C.J.J. Haertel, J. Evanko, The status quo of DAC projects worldwide. Chem **9**, 3381–3384 (2023)
6. M. Zeeshan, M.K. Kidder, E. Pentzer, R.B. Getman, B. Gurkan, Direct air capture of CO2: from insights into the current and emerging approaches to future opportunities. Front. Sustai. **4**, 1167713 (2023)
7. J. Young, N. McQueen, C. Charalambous, S. Foteinis, O. Hawrot, M. Ojeda, H. Pilorgé, J. Andresen, P. Psarras, P. Renforth, The cost of direct air capture and storage can be reduced via strategic deployment but is unlikely to fall below stated cost targets. One Earth **6**, 899–917 (2023)
8. H. Herzog, Direct air capture. Greenh. Gas Remov. Technol. **31**, 115 (2022)
9. S. Fuss, W.F. Lamb, M.W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. de Oliveira Garcia, J. Hartmann, T. Khanna, Negative emissions—Part 2: Costs, potentials and side effects. Environ. Res. Lett. **13**, 063002 (2018)
10. ENERGY, T.S. Fans and Blowers: Costs and Energy Consumption? https://thundersaidenergy.com/downloads/fans-and-blowers-costs-and-energy-consumption/. Accessed 29 April 2024
11. Climeworks. Orca: The First Large-Scale Plant. https://climeworks.com/plant-orca. Accessed 29 April 2024
12. Plumer, B. (2023). In a U.S. First, a Commercial Plant Starts Pulling Carbon From the Air. https://www.nytimes.com/2023/11/09/climate/direct-air-capture-carbon.html. Accessed 29 April 2024
13. G. Leonzio, P.S. Fennell, N. Shah, A comparative study of different sorbents in the context of direct air capture (DAC): Evaluation of key performance indicators and comparisons. Appl. Sci. **12**, 2618 (2022)
14. C.J.E. Bajamundi, J. Koponen, V. Ruuskanen, J. Elfving, A. Kosonen, J. Kauppinen, J. Ahola, Capturing CO2 from air: Technical performance and process control improvement. J. CO2 Utiliz. **30**, 232–239 (2019)

15. M. Erans, E.S. Sanz-Pérez, D.P. Hanak, Z. Clulow, D.M. Reiner, G.A. Mutch, Direct air capture: Process technology, techno-economic and socio-political challenges. Energy Environ. Sci. **15**, 1360–1405 (2022)
16. L. Küng, S. Aeschlimann, C. Charalambous, F. McIlwaine, J. Young, N. Shannon, K. Strassel, C.N. Maesano, R. Kahsar, D. Pike, A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage. Energy Environ. Sci. **16**, 4280–4304 (2023)
17. S. Deutz, A. Bardow, Life-cycle assessment of an industrial direct air capture process based on temperature-vacuum swing adsorption. Nat. Energy **6**, 203–213 (2021)
18. G. Leonzio, P.S. Fennell, N. Shah, Analysis of technologies for carbon dioxide capture from the air. Appl. Sci. **12**, 8321 (2022)
19. M. Bui, C.S. Adjiman, A. Bardow, E.J. Anthony, A. Boston, S. Brown, P.S. Fennell, S. Fuss, A. Galindo, L.A. Hackett, Carbon capture and storage (CCS): The way forward. Energy Environ. Sci. **11**, 1062–1176 (2018)
20. M. Ozkan, A.-A. Akhavi, W.C. Coley, R. Shang, Y. Ma, Progress in carbon dioxide capture materials for deep decarbonization. Chem **8**, 141–173 (2022)
21. M. Ozkan, K.A. Quiros, J.M. Watkins, T.M. Nelson, N.D. Singh, M. Chowdhury, T. Namboodiri, K.R. Talluri, E. Yuan, Curbing pollutant CO2 by using two-dimensional MXenes and MBenes. Chem (2023). https://doi.org/10.1016/j.chempr.2023.09.001
22. M. Ozkan, R. Custelcean, The status and prospects of materials for carbon capture technologies. MRS Bull. **47**, 390–394 (2022)
23. Ozkan, M. (2024). MXenes vs MBenes: Demystifying the materials of tomorrow's carbon capture revolution. MRS Energy & Sustainability.
24. D.W. Keith, G. Holmes, D.S. Angelo, K. Heidel, A process for capturing CO2 from the atmosphere. Joule **2**, 1573–1594 (2018)
25. N. McQueen, M.J. Desmond, R.H. Socolow, P. Psarras, J. Wilcox, Natural gas vs. electricity for solvent-based direct air capture. Front. Climate **2**, 618644 (2021)
26. K. An, K. Li, C.-M. Yang, J. Brechtl, K. Nawaz, A comprehensive review on regeneration strategies for direct air capture. J. CO2 Utiliz. **76**, 102587 (2023)
27. S. Li, S. Deng, L. Zhao, W. Xu, X. Yuan, Z. Guo, Z. Du, Energy dissipation evaluation of temperature swing adsorption (TSA) cycle based on thermodynamic entropy insights. Sci. Rep. **9**, 16599 (2019)
28. U.S. Department of Energy, N.E.T.L. (2022). Carbon Capture Program R&D: Compendium of Carbon Capture Technology. https://netl.doe.gov/sites/default/files/2022-09/0919-Carbon-Capture-Technology-Compendium-2022.pdf. Accessed 29 April 2024
29. IEA (2020). CCUS in Clean Energy Transitions. https://www.iea.org/reports/ccus-in-clean-energy-transitions. Accessed 29 April 2024
30. K.S. Lackner, The thermodynamics of direct air capture of carbon dioxide. Energy **50**, 38–46 (2013)
31. R.P. Lively, M.J. Realff, On thermodynamic separation efficiency: Adsorption processes. AIChE J. **62**, 3699–3705 (2016)
32. X. Wu, R. Krishnamoorti, P. Bollini, Technological options for direct air capture: A comparative process engineering review. Annu. Rev. Chem. Biomol. Eng. **13**, 279–300 (2022)
33. IEA (2023). Carbon Capture, Utilisation and Storage. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage. Accessed 29 April 2024
34. L.-X. Ren, F.-L. Chang, D.-Y. Kang, C.-L. Chen, Hybrid membrane process for post-combustion CO2 capture from coal-fired power plant. J. Membr. Sci. **603**, 118001 (2020)
35. L.W. Yue, M. Liu, J. Wang, J. Yan, Performance analysis of coal-fired power plants integrated with carbon capture system under load-cycling operation conditions. Energy (2023). https://doi.org/10.1016/j.energy.2023.127532
36. K. Madhu, S. Pauliuk, S. Dhathri, F. Creutzig, Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. Nat. Energy **6**, 1035–1044 (2021)
37. S. Jackson, E. Brodal, *A Comparison of the Energy Consumption for CO2 Compression Process alternatives* (IOP Publishing, Bristol, 2018)
38. Chauvy, R., Dubois, L., Thomas, D., and De Weireld, G. (2021). Techno-economic and environmental assessment of carbon capture at a cement plant and CO2 utilization in production of synthetic natural gas. pp. 15–18.
39. Daniels, J. (2022). Global Status of CCS 2022. https://status22.globalccsinstitute.com/wp-content/uploads/2022/10/Global-Status-of-CCS-2022-Report-Final-compressed.pdf. Accessed 29 April 2024
40. Gokhan, A. (2021). An Advanced Sorbent for Direct Air Capture. https://www.osti.gov/biblio/1779280. Accessed 29 April 2024
41. L. Jiang, W. Liu, R. Wang, A. Gonzalez-Diaz, M. Rojas-Michaga, S. Michailos, M. Pourkashanian, X. Zhang, C. Font-Palma, Sorption direct air capture with CO2 utilization. Prog. Energy Combust. Sci. **95**, 101069 (2023)
42. C.J.J. Haertel, M. McNutt, M. Ozkan, E.S. Aradóttir, K.T. Valsaraj, P.R. Sanberg, S. Talati, J. Wilcox, The promise of scalable direct air capture. Chem **7**, 2831–2834 (2021)
43. A.N. Antzaras, T. Papalas, E. Heracleous, C. Kouris, Techno–economic and environmental assessment of CO2 capture technologies in the cement industry. J. Clean. Prod. **428**, 139330 (2023)
44. Y. Wang, H. Chen, H. Wang, G. Xu, J. Lei, Q. Huang, T. Liu, Q. Li, A novel carbon dioxide capture system for a cement plant based on waste heat utilization. Energy Convers. Manage. **257**, 115426 (2022)
45. Alberici S., Mir G.U.R., Stork M., Wiersma F., Dowell N.M., Shah N, Fennell P. (2017). Assessing the Potential of Co2 Utilisation in The UK (Final Report). https://assets.publishing.service.gov.uk/media/5cc9bd9c40f0b64c1e187664/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2__1_.pdf. Accessed 29 April 2024
46. Greenhouse Gases Equivalencies Calculator - Calculations and References. (2023). https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references. Accessed 29 April 2024
47. Raimund Malischek, S.M. (2021). The World has Vast capacity to Store CO2: Net Zero Means We'll Need It. https://www.iea.org/commentaries/the-world-has-vast-capacity-to-store-co2-net-zero-means-we-ll-need-it. Accessed 29 April 2024
48. Collins, L. (2021). The Amount of Energy Required by Direct Air Carbon Capture Proves it is an Exercise in Futility. https://www.rechargenews.com/energy-transition/the-amount-of-energy-required-by-direct-air-carbon-capture-proves-it-is-an-exercise-in-futility/2-1-1067588. Accessed 29 April 2024.
49. R. Custelcean, N.J. Williams, K.A. Garrabrant, P. Agullo, F.M. Brethomé, H.J. Martin, M.K. Kidder, Direct air capture of CO2 with aqueous amino acids and solid bis-iminoguanidines (BIGs). Ind. Eng. Chem. Res. **58**, 23338–23346 (2019)
50. S. Seo, M. Quiroz-Guzman, M.A. DeSilva, T.B. Lee, Y. Huang, B.F. Goodrich, W.F. Schneider, J.F. Brennecke, Chemically tunable ionic liquids with aprotic heterocyclic anion (AHA) for CO2 capture. J. Phys. Chem. B **118**, 5740–5751 (2014)
51. S. Choi, T. Watanabe, T.-H. Bae, D.S. Sholl, C.W. Jones, Modification of the Mg/DOBDC MOF with amines to enhance CO2 adsorption from ultradilute gases. J. Phys. Chem. Lett. **3**, 1136–1141 (2012)
52. T.M. McDonald, W.R. Lee, J.A. Mason, B.M. Wiers, C.S. Hong, J.R. Long, Capture of carbon dioxide from air and flue gas in the

alkylamine-appended metal-organic framework mmen-Mg2 (dobpdc). J. Am. Chem. Soc. **134**, 7056–7065 (2012)
53. L.A. Darunte, A.D. Oetomo, K.S. Walton, D.S. Sholl, C.W. Jones, Direct air capture of CO2 using amine functionalized MIL-101 (Cr). ACS Sustai. Chem. Eng. **4**, 5761–5768 (2016)
54. Rives, K. (2021). Vacuuming Carbon from the Sky No Joke for Rapidly Warming World. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/vacuuming-carbon-from-the-sky-no-joke-for-rapidly-warming-world-65333217. Accessed 29 April 2024
55. F. Sabatino, A. Grimm, F. Gallucci, M. van Sint Annaland, G.J. Kramer, M. Gazzani, A comparative energy and costs assessment and optimization for direct air capture technologies. Joule **5**, 2047–2076 (2021)
56. Ozkan, M., Anvaya, B.N., Thrayesh, N., Yijian, C., Matheshwaran, B., Joan, S.E.J., Yingfan, G., Sameeha, T., Jason, L., Kamal, R.T., Ruoxu, S., Cengiz, S.O., Jordyn, M.W. (2024). Forging a Sustainable Sky: Unveiling the Pillars of Aviation e-Fuel Production for Carbon Emission Circularity. Iscience.
57. A.S. Mihrimah Ozkan, T. Nadezda Kongi, A. Hatton, S. Oldham, E. Sanders, Electrochemical direct air capture and direct ocean capture: The next frontier in carbon removal. Chem **10**, 3–6 (2024)