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REVIEW

Powering Direct Air Capture: Overview of Existing Concepts and the Overlooked Role of Concentrated Solar Thermal Technologies

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Abstract

Purpose of Review This review aims to summarize the different energy sources that have been proposed to power direct air capture (DAC) of CO_2, to assess their maturity and to suggest overlooked concepts.

Recent Findings Among the concepts based on renewable energy, the authors found that concentrated solar thermal (CST) technologies have been largely overlooked, even though they are the most cost-effective source of renewable dispatchable heat.

Summary
Identifying energy sources for DAC that are both scalable and low in carbon intensity remains a major challenge for widespread deployment. Promising options have been identified, such as nuclear and curtailable renewables, as well as a growing interest in power-to-heat and fully electric solutions, and a research gap in the potential of CST technologies to power DAC systems.

Introduction

Direct air capture of CO_2 (DAC) refers to the set of technologies that can capture carbon dioxide from the atmosphere by physically or chemically removing CO_2 molecules without involving any biological process [1–3]. The application of DAC depends on the final use of the captured CO_2. On the one hand, if carbon dioxide is permanently sequestered (DACS), it can be considered as a carbon dioxide removal (CDR) technology, providing negative emissions that can offset unavoidable emissions or remove previously emitted CO_2 [4–6]. On the other hand, captured CO_2 can be utilized as a feedstock for synthetic fuels or chemicals (DACU), which alongside with biofuels, are critical to decarbonize certain sectors such as long-haul aviation or maritime transport [7–9].

Due to the low concentration of CO_2 in the atmosphere (currently above 420 ppm [10]), DAC requires a much higher energy input than carbon capture from industrial sources [11–13]. For this reason, there is a consensus in the CDR scientific community that DACS should not be perceived as an alternative to avoiding and sequestering fossil CO_2emissions from hard-to-abate industrial sectors [3, 14–17]. However, it seems clear that CDR and synthetic fuels will become key technologies in the energy transition [6, 18]. In this context, DAC is a particularly relevant technology due to its capacity to provide high purity CO_2 for both sequestration and utilization without the biophysical limitations of other technologies [19–21].

Life cycle assessments have shown that due to the high energy demand of the DAC, it must be powered by energy sources with very low carbon intensities to avoid the indirect emissions of energy production reducing the overall carbon removal efficiency (possibly even resulting in positive emissions) [22–25]. For this reason, the search for low-carbon energy sources and their combination with DAC remains one of the main focuses of research in the field [26, 27]. This review aims to provide an overview of energy sources and integrations that have been proposed to date and to highlight some knowledge gaps that, to the best of the authors' knowledge, have not yet been addressed.

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Current Energy Sources

In order to understand the energy sources currently in use in existing DAC systems, it is necessary to have a closer look at the technology. To date, there are two mature approaches: liquid DAC (L-DAC) and solid DAC (S-DAC) [3, 28]. L-DAC relies on chemical absorption of CO_2 with a liquid solution, usually containing alkali salts. The carbon dioxide reacts with the hydroxides to form carbonates, which are precipitated in a step following the air contactor. These carbonates are then calcined, requiring temperatures around 900 °C for calcium carbonate [29]. The main energy demand of this process is high-temperature heat (5.25–8.1 GJ/t CO_2) and electricity to drive the fans and compress the obtained CO_2 (1.32–1.8 GJ/t CO_2) [30]. Existing pilot and first-of-a-kind plants use a direct-fired calciner with an oxyfuel mixture of natural gas for heat input and a natural gas turbine for electricity supply [29, 30]. Thanks to the process design, the fossil CO_2 resulting from the natural gas combustion is immediately captured and mixed with atmospheric CO_2. Nevertheless, indirect greenhouse gas emissions can be significantly affected by methane leakage along the supply chain [31, 32]. S-DAC, on the other hand, relies on solid sorbents to adsorb CO_2 molecules. Sorbent development remains a major research topic (and a trade secret for many companies), but according to available data, most existing S-DAC systems use amine-functionalized porous materials [33–35]. In general, S-DAC has similar energy requirements as L-DAC (2.9–5.5 GJ/t CO_2 for heat and 0.6–1.1 GJ/t CO_2 for electricity), with the advantage of significantly lower temperature requirements, as CO_2 desorption requires heat at around 100 °C [3, 30]. Therefore, existing S-DAC projects (which are currently much more diverse than L-DAC projects) use geothermal or industrial waste heat and grid electricity, as they are generally located in countries with remarkably low-carbon electricity grids [30, 36, 37].

Prospective Energy Sources

In the face of a likely scenario requiring rapid scale-up and deployment of DAC, many authors have envisioned different ways to provide low-carbon heat and electricity. In the case of L-DAC, this endeavor is particularly complicated because the technologies that can supply low-carbon heat at very high temperatures are limited [3]. The literature review has shown that, in addition to natural gas combustion, calciners powered by (1) biomethane, (2) electricity, (3) hydrogen, (4) concentrated solar energy and (5) nuclear energy have also been explored. Biomethane is a relatively straightforward solution for decoupling L-DAC from fossil fuels, although its availability for large-scale use may be limited [38, 39]. Therefore, electric calciners appear to be the preferred option to date, as they are readily available, although not yet at the scale required by a large L-DAC facility [31, 40, 41]. Other authors have instead proposed the use of hydrogen-fueled calciners, including hybrid concepts in which hydrogen is both combusted and consumed in a fuel cell to power indirect electric heating for the calciner [42, 43]. Alternatively, a study published by the authors suggested the use of a solar calciner, inspired by previous works on solar calcium looping [44–46]. The direct use of nuclear energy in the calciner has been mentioned as a possibility, but to the best of the authors' knowledge it has not been studied in detail [47]. Notably, none of the aforementioned alternatives are currently planned to be deployed in near-future L-DAC plants [48, 49]. However, an electric calciner is under development by a company investigating the passive carbonation of calcium hydroxide [50].

Due to the comparatively much lower operating temperatures for S-DAC, it is easier to find suitable energy sources. As a result, the literature considers a broader range of options that can be grouped into three basic categories: S-DAC powered by (1) waste heat, (2) non-renewable sources, and (3) renewable sources. Among these categories, waste heat represents the best-case scenario for S-DAC because, if available at the right temperature, it translates into free heat with no associated environmental burdens. However, the availability of such waste heat sources is limited and, while feasible in some areas, may not allow for massive deployment of DAC [51, 52]. Some studies have considered the downstream utilization of CO_2 for synthetic fuel production and have shown that waste heat from these processes could partially power S-DAC [53–55]. If waste heat is not available, non-renewable energy sources could be the most cost-effective solutions for S-DAC (even when indirect emissions are taken into account), with the added benefit of co-producing electricity [56]. This is especially true for nuclear-based concepts that use both electricity and steam produced in nuclear reactors [47, 56, 57]. Similarly, powering DAC with a combined cycle gas turbine with CCS could also be competitive [38, 56, 58]. In both cases, DAC systems benefit from high capacity factors, but these approaches also face potential challenges: the nuclear option may be hindered by high capital costs, social acceptance and national legislations, while gas-powered S-DAC systems are vulnerable to indirect emissions from methane leakage and fluctuations in natural gas prices [56]. Finally, renewable-based S-DAC can be divided into two subcategories: systems using renewable heat or fully electric concepts. On the one hand, systems using renewable heat normally rely on geothermal energy, although biomethane [38] and solar heat collected with a linear Fresnel [24] have also been considered in literature. On the other hand, fully electric solutions rely on power-to-heat systems such as electric heaters

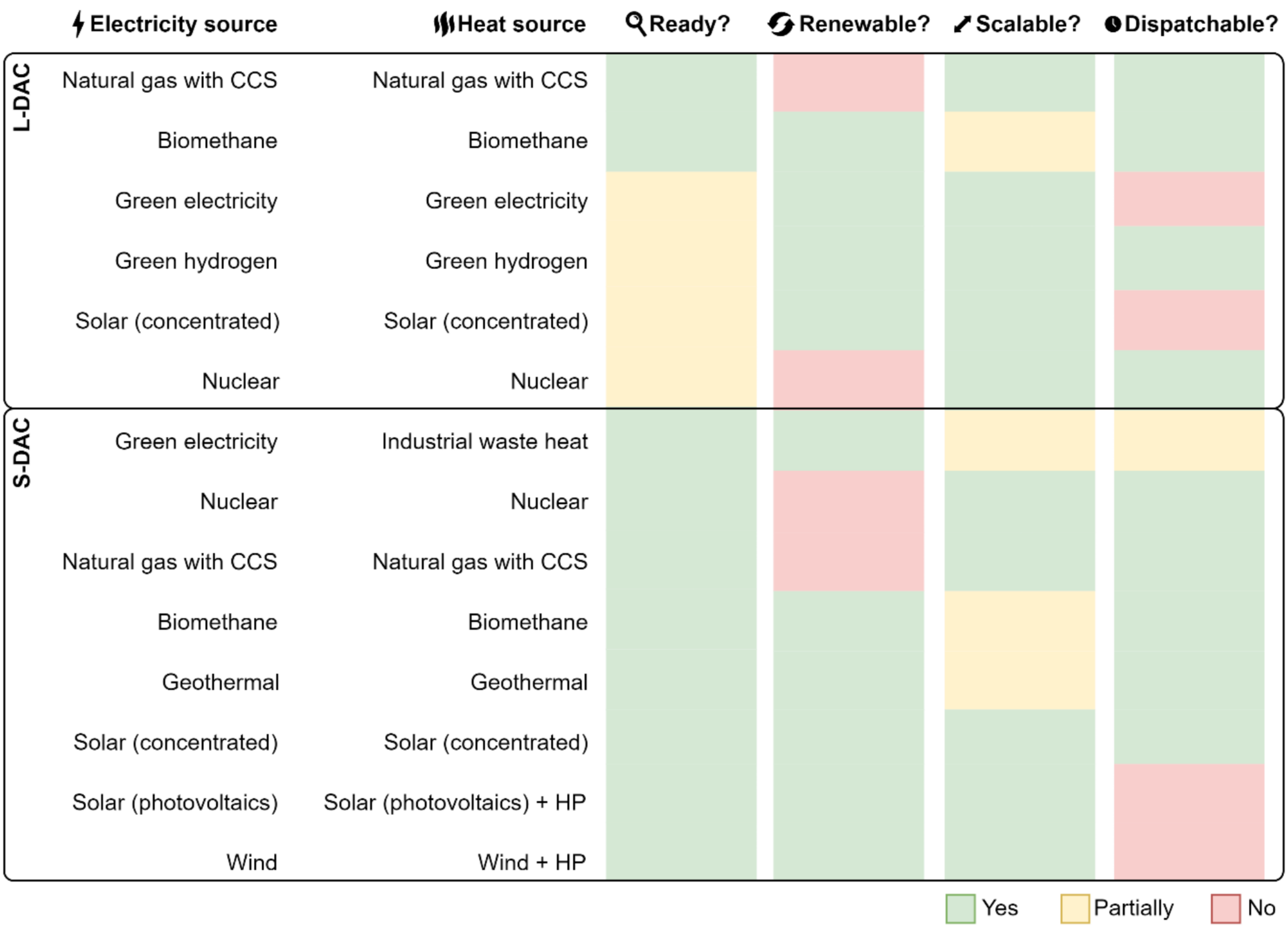

Fig. 1 Overview of power alternatives for liquid and solid direct air capture (L-DAC and S-DAC, respectively). Acronyms: "CCS" (carbon capture and storage) and "HP" (heat pump). Concentrated solar power is non-dispatchable for L-DAC due to challenges in storing heat at the high temperatures required, while it is dispatchable for S-DAC

or high-temperature heat pumps to produce the heat at the desired temperature. This approach has been considered in many recent studies that have shown the possibility of using battery energy storage to increase the capacity factor of the system when powered directly by renewable electricity from photovoltaic or wind turbines [59–61]. Recent work has also shown the potential of using curtailed electricity to power DAC, which could be economically feasible despite a relatively low capacity factor [62–64]. An overview of the alternatives for powering S-DAC and L-DAC is shown in Fig. 1.

Concentrated Solar Thermal Technologies To Power DAC

The performed literature review shows an interest towards fully electric concepts using power-to-heat systems, which is further confirmed by the ongoing efforts to develop electrochemical regeneration processes for both S-DAC and L-DAC that would not require any heat input [65, 66]. However, there are two fundamental arguments against replacing heat demand with electricity in DAC. First, heat can be harvested with higher efficiencies than electricity can be produced, and as a result, heat generally has a lower cost and environmental footprint than electricity. Second, storing heat, especially at the temperatures relevant to S-DAC, remains more economical and scalable than storing electricity [67]. Based on these principles, concentrated solar thermal (CST) technologies can provide dispatchable renewable heat that is both significantly cheaper and has a lower carbon intensity than power-to-heat systems powered by photovoltaics or wind energy [68, 69]. In addition, unlike power-to-heat concepts, CST technologies and thermal energy storage do not require any of the most critical raw materials for the energy transition [70]. Therefore, from the authors' perspective, a research gap exists in the comprehensive integration of different CST technologies with S-DAC.

As with any other renewable energy source, it is important to consider how local environmental factors may limit the optimal locations for the system, as optimal conditions for DAC may not coincide with optimal conditions for renewable energy [71–74]. It is also important to consider that using renewable energy to power DAC systems may not be the most effective method of reducing emissions in many locations. Rather, this low-carbon energy could be better utilized to replace more carbon-intensive energy sources [75].

Conclusion

The supply of heat and electricity for DAC remains a challenge due to the high demand for energy with very low carbon intensity. The landscape of alternatives to the natural gas calciner for L-DAC is still very limited, with only a few concepts involving electric, hydrogen and solar powered calciners, but still far from large-scale deployment. For S-DAC, by contrast, there is a much broader and commercially mature range of alternatives that have been extensively explored in the literature. However, the present review has identified that the possibility of powering S-DAC with CST technologies has been largely overlooked. The main advantage of CST is that it offers the lowest cost of dispatchable renewable heat with very low associated greenhouse gas emissions. Additionally, CST designs with decades of operational experience would require minimal technical modifications to power S-DAC at high capacity factors with co-production of electricity. The reason for the lack of integration of DAC with CST technologies may be that CST technologies have lagged behind other renewables in global deployment, primarily due to higher upfront capital costs and limited modularity, which have slowed their learning curve. However, DAC plants must be located close to CO_2 consumers or sequestration sites, requiring them to be relatively large and centralized facilities. These characteristics are particularly well suited to both stand-alone CST technologies and hybrid CST systems that integrate other renewable energy sources. Accordingly, the authors advise focusing efforts on integrating CST and DAC by identifying the most effective configurations, scales, and regions.

Key References

[56] One of the most recent and comprehensive studies on the impact of location and energy sources from an economic and environmental perspective for S-DAC. The authors consider a wide range of energy sources with very detailed models.

[59] An innovative study on the integration of intermittent renewable energy into DAC operations. It considers multiple sites and identifies optimal S-DAC system designs including energy storage that optimize economic and environmental impacts.

[63] An interesting work that explores more flexible designs and operational strategies for S-DACs to facilitate its integration with intermittent renewable energy, thus contributing to grid stability.

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Declarations

Competing Interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

1. Lackner KS. Capture of carbon dioxide from ambient air. Eur Phys J Spec Top. 2009;176:93–106. https://doi.org/10.1140/epjst/e2009-01150-3.
2. Physics AP. Direct air capture of CO2 with chemicals: A technology assessment for the APS panel on public affairs. APS Phys. 2011.
3. International Energy Agency (IEA). Direct air capture: A key technology for net zero. France; 2022.
4. Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration, Board on Atmospheric Sciences and Climate. Board on energy and environmental systems, board on agriculture and natural resources, board on Earth sciences and resources, board on chemical sciences and technology. et al. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington (DC); 2018.
5. McQueen N, Psarras P, Pilorgé H, Liguori S, He J, Yuan M, et al. Cost analysis of direct air capture and sequestration coupled

to Low-Carbon thermal energy in the united States. Environ Sci Technol. 2020;54:7542–51. https://doi.org/10.1021/acs.est.0c00476.
6. Naomi Vaughan S, Fuss H, Buck F, Schenuit J, Pongratz I, Schulte, et al. The state of carbon dioxide removal.– 2nd Edition: OSF; 2024.
7. Brazzola N, Moretti C, Sievert K, Patt A, Lilliestam J. Utilizing CO_2 as a strategy to scale up direct air capture May face fewer short-term barriers than directly storing CO_2. Environ Res Lett. 2024;19:54037. https://doi.org/10.1088/1748-9326/ad3b1f.
8. Rojas-Michaga MF, Michailos S, Cardozo E, Akram M, Hughes KJ, Ingham D, Pourkashanian M. Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment. Energy Conv Manag. 2023;292:117427. https://doi.org/10.1016/j.enconman.2023.117427.
9. Bruhn T, Naims H, Olfe-Kräutlein B. Separating the debate on CO_2 utilisation from carbon capture and storage. Environ Sci Policy. 2016;60:38–43. https://doi.org/10.1016/j.envsci.2016.03.001.
10. Tans P, Keeling R. Mauna Loa CO_2 monthly mean data. 2024. https://gml.noaa.gov/ccgg/trends/. Accessed 15 Feb 2023.
11. Wilcox J. Carbon capture. New York, NY: Springer New York; 2012.
12. Fasihi M, Efimova O, Breyer C. Techno-economic assessment of CO_2 direct air capture plants. J Clean Prod. 2019;224:957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.
13. Zuberi MJS, Shehabi A, Rao P. Cross-sectoral assessment of CO_2 capture from U.S. Industrial flue gases for fuels and chemicals manufacture. Int J Greenhouse Gas Control. 2024;135:104137. https://doi.org/10.1016/j.ijggc.2024.104137.
14. Della Vigna M, Stavrinou Z, Gandolfi A, Showdon N, Young P, Tylenda E et al. Carbonomics: Introducing the GS net zero carbon models and sector frameworks; 2021.
15. Intergovernmental Panel on Climate Change. Working group III-Mitigation of climate change. CDR Factsheet: Carbon Dioxide Removal.
16. Sekera J, Cagalanan D, Swan A, Birdsey R, Goodwin N, Lichtenberger A. Carbon dioxide removal–What's worth doing? A biophysical and public need perspective. PLOS Clim. 2023;2:e0000124. https://doi.org/10.1371/journal.pclm.0000124.
17. Malm A, Carton W. Seize the means of carbon removal: the political economy of direct air capture. Hist Mater. 2021;29:3–48. https://doi.org/10.1163/1569206X-29012021.
18. United Nations Environment Programme. Emissions gap report 2023: broken Record– Temperatures hit new highs, yet world fails to cut emissions (again). Nairobi: United Nations Environment Programme.
19. Smith P, Davis SJ, Creutzig F, Fuss S, Minx J, Gabrielle B, et al. Biophysical and economic limits to negative CO_2 emissions. Nat Clim Change. 2016;6:42–50. https://doi.org/10.1038/nclimate2870.
20. Hanna R, Abdulla A, Xu Y, Victor DG. Emergency deployment of direct air capture as a response to the climate crisis. Nat Commun. 2021. https://doi.org/10.1038/s41467-020-20437-0.
21. Shi X, Xiao H, Azarabadi H, Song J, Wu X, Chen X, Lackner KS. Sorbents for the direct capture of CO_2 from ambient air. Angew Chem Int Ed Engl. 2020;59:6984–7006. https://doi.org/10.1002/anie.201906756.
22. Deutz S, Bardow A. Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Nat Energy. 2021;6:203–13. https://doi.org/10.1038/s41560-020-00771-9.
23. Madhu K, Pauliuk S, Dhathri S, Creutzig F. Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. Nat Energy. 2021;6:1035–44. https://doi.org/10.1038/s41560-021-00922-6.
24. Terlouw T, Treyer K, Bauer C, Mazzotti M. Life cycle assessment of direct air carbon capture and storage with Low-Carbon energy sources. Environ Sci Technol. 2021. https://doi.org/10.1021/acs.est.1c03263.
25. Ottenbros AB, van Zelm R, Simons J, van der Hulst MK, de Kleijne K, de Neve H, Huijbregts MAJ. Prospective environmental burdens and benefits of fast-swing direct air carbon capture and storage. Sci Rep. 2024;14:16549. https://doi.org/10.1038/s41598-024-66990-2.
26. Ozkan M. Atmospheric alchemy: the energy and cost dynamics of direct air carbon capture. MRS Energy Sustain. 2024. https://doi.org/10.1557/s43581-024-00091-5.
27. Günther P, Ekardt F. Human rights and Large-Scale carbon dioxide removal: potential limits to BECCS and DACCS deployment. Land. 2022;11:2153. https://doi.org/10.3390/land11122153.
28. McQueen N, Gomes KV, McCormick C, Blumanthal K, Pisciotta M, Wilcox J. A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. Prog Energy. 2021;3:32001. https://doi.org/10.1088/2516-1083/abf1ce.
29. Keith D, Holmes G, St. Angelo D, Heidel K. A Process for Capturing CO_2 from the Atmosphere. Joule. 2018. https://doi.org/10.1016/j.joule.2018.05.006
30. Ozkan M, Nayak SP, Ruiz AD, Jiang W. Current status and pillars of direct air capture technologies. iScience. 2022;25:103990. https://doi.org/10.1016/j.isci.2022.103990.
31. McQueen N, Desmond MJ, Socolow RH, Psarras P, Wilcox J. Natural gas vs. Electricity for Solvent-Based direct air capture. Front Clim. 2021. https://doi.org/10.3389/fclim.2020.618644.
32. Küng L, Aeschlimann S, Charalambous C, McIlwaine F, Young J, Shannon N, et al. A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage. Energy Environ Sci. 2023;16:4280–304. https://doi.org/10.1039/d3ee01008b.
33. Balasubramaniam BM, Thierry P-T, Lethier S, Pugnet V, Llewellyn P, Rajendran A. Process-performance of solid sorbents for direct air capture (DAC) of CO_2 in optimized temperature-vacuum swing adsorption (. TVSA) cycles; 2023.
34. Gebald C, Wurzbacher JA, Tingaut P, Zimmermann T, Steinfeld A. Amine-Based nanofibrillated cellulose as adsorbent for CO_2 capture from air. Environ Sci Technol. 2011;45:9101–8. https://doi.org/10.1021/es202223p.
35. Charalambous C, Moubarak E, Schilling J, Sanchez Fernandez E, Wang J-Y, Herraiz L, et al. A holistic platform for accelerating sorbent-based carbon capture. Nature. 2024. https://doi.org/10.1038/s41586-024-07683-8.
36. Erans M, Sanz-Pérez ES, Hanak DP, Clulow Z, Reiner DM, Mutch GA. Direct air capture: process technology, techno-economic and socio-political challenges. Energy Environ Sci. 2022;15:1360–405. https://doi.org/10.1039/D1EE03523A.
37. Bisotti F, Hoff KA, Mathisen A, Hovland J. Direct air capture (DAC) deployment: A review of the industrial deployment. Chem Eng Sci. 2024;283:119416. https://doi.org/10.1016/j.ces.2023.119416.
38. Qiu Y, Lamers P, Daioglou V, McQueen N, de Boer H-S, Harmsen M, et al. Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100. Nat Commun. 2022;13:3635. https://doi.org/10.1038/s41467-022-31146-1.
39. Heck V, Gerten D, Lucht W, Popp A. Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nat Clim Change. 2018;8:151–5. https://doi.org/10.1038/s41558-017-0064-y.
40. Shorey P, Abdulla A. Liquid solvent direct air capture's cost and carbon dioxide removal vary with ambient environmental

conditions. Commun Earth Environ. 2024. https://doi.org/10.1038/s43247-024-01773-1.
41. Liu CM, Sandhu NK, McCoy ST, Bergerson JA. A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production. Sustainable Energy Fuels. 2020;4:3129–42. https://doi.org/10.1039/C9SE00479C.
42. Griffiths I, Wang R, Ling-Chin J, Paul Roskilly A. Solid oxide fuel cells with integrated direct air carbon capture: A techno-economic study. Energy Conv Manag. 2024;315:118739. https://doi.org/10.1016/j.enconman.2024.118739.
43. Mostafa M, Antonicelli C, Varela C, Barletta D, Zondervan E. Capturing CO_2 from the atmosphere: design and analysis of a large-scale DAC facility. Carbon Capture Sci Technol. 2022;4:100060. https://doi.org/10.1016/j.ccst.2022.100060.
44. Prats-Salvado E, Jagtap N, Monnerie N, Sattler C. Solar-Powered direct air capture: Techno-Economic and environmental assessment. Environ Sci Technol. 2024. https://doi.org/10.1021/acs.est.3c08269.
45. Arwa EO, Schell KR. Batteries or silos: optimizing storage capacity in direct air capture plants to maximize renewable energy use. Appl Energy. 2024;355:122345. https://doi.org/10.1016/j.apenergy.2023.122345.
46. Moumin G, Ryssel M, Zhao L, Markewitz P, Sattler C, Robinius M, Stolten D. CO_2 emission reduction in the cement industry by using a solar calciner. Renewable Energy. 2019;145:1578–96. https://doi.org/10.1016/j.renene.2019.07.045.
47. Stauff NE, Mann WN, Moisseytsev A, Durvasulu V, Mantripragada H, Fout T. Assessment of Nuclear Energy to Support Negative Emission Technologies; 2023.
48. Investor Update OXYLCV. 2022. https://www.oxy.com/investors/stockholder-resources/lcv-investor-update/. Accessed 28 Sep 2022.
49. Liekens I, Ramón Hernández M, Stoefs W. Net zero oil company: climate action or oxymoron?? Assessing the climate strategy of occidental petroleum. Oxy); 2024.
50. McQueen N, Ghoussoub M, Mills J, Scholten M. A scalable direct air capture process based on accelerated weathering of calcium hydroxide; 2022.
51. Abramson E, McFarlane D, Jordan A, Rodriguez D, Ogland-Hand J, Holwerda N. An atlas of direct air capture. Opportunities for Negative Emissions in the United States; 2023.
52. Terlouw T, Pokras D, Becattini V, Mazzotti M. Assessment of potential and Techno-Economic performance of solid sorbent direct air capture with CO_2 storage in Europe. Environ Sci Technol. 2024;58:10567–81. https://doi.org/10.1021/acs.est.3c10041.
53. Prats-Salvado E, Monnerie N, Sattler C. A techno-economic and environmental evaluation of the integration of direct air capture with hydrogen derivatives production. Int J Hydrog Energy. 2024. https://doi.org/10.1016/j.ijhydene.2024.10.026.
54. Fasihi M, Breyer C. Global production potential of green methanol based on variable renewable electricity. Energy Environ Sci. 2024;17:3503–22. https://doi.org/10.1039/D3EE02951D.
55. Cameli F, Delikonstantis E, Kourou A, Rosa V, van Geem KM, Stefanidis GD. Conceptual process design and technoeconomic analysis of an e-Methanol plant with direct Air-Captured CO 2 and electrolytic H 2. Energy Fuels. 2024;38:3251–61. https://doi.org/10.1021/acs.energyfuels.3c04147.
56. Sendi M, Bui M, Mac Dowell N, Fennell P. Geospatial techno-economic and environmental assessment of different energy options for solid sorbent direct air capture. Cell Rep Sustain. 2024;1:100151. https://doi.org/10.1016/j.crsus.2024.100151.
57. Bertoni L, Roussanaly S, Riboldi L, Anantharaman R, Gazzani M. Integrating direct air capture with small modular nuclear reactors: Understanding performance, cost, and potential. J Phys Energy. 2024. https://doi.org/10.1088/2515-7655/ad2374.
58. National Academies of. Sciences, Engineering, and Medicine. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda 2019. https://doi.org/10.17226/25259
59. Gutsch M, Leker J. Co-assessment of costs and environmental impacts for off-grid direct air carbon capture and storage systems. Commun Eng. 2024. https://doi.org/10.1038/s44172-023-00152-6.
60. Datta A, Krishnamoorti R. Analysis of direct air capture integrated with wind energy and enhanced oil recovery. Environ Sci Technol. 2023;57:2084–92. https://doi.org/10.1021/acs.est.2c05194%26;ref=pdf.
61. Wiegner JF, Grimm A, Weimann L, Gazzani M. Optimal design and operation of solid sorbent direct air capture processes at varying ambient conditions. Ind Eng Chem Res. 2022;61:12649–67. https://doi.org/10.1021/acs.iecr.2c00681.
62. Yang L, Wu X. Net-zero carbon configuration approach for direct air carbon capture based integrated energy system considering dynamic characteristics of CO_2 adsorption and desorption. Appl Energy. 2024;358:122608. https://doi.org/10.1016/j.apenergy.2023.122608.
63. Liu Y, Miao Y, Feng Y, Wang L, Fujikawa S, Yu L. Wind curtailment powered flexible direct air capture. Appl Energy. 2025;377:124402. https://doi.org/10.1016/j.apenergy.2024.124402.
64. Liu Y, Miao Y, Wang L, Gu X, Li Z, Fujikawa S, Yu L. Addressing solar power curtailment by integrating flexible direct air capture. Carbon Capture Sci Technol. 2025;14:100304. https://doi.org/10.1016/j.ccst.2024.100304.
65. Rosen N, Welter A, Schwankl M, Plumeré N, Staudt J, Burger J. Assessment of the potential of electrochemical steps in direct air capture through Techno-Economic analysis. Energy Fuels. 2024;38:15469–81. https://doi.org/10.1021/acs.energyfuels.4c02202.
66. Gutiérrez-Sánchez O, de Mot B, Daems N, Bulut M, Vaes J, Pant D, Breugelmans T. Electrochemical conversion of CO 2 from direct air capture solutions. Energy Fuels. 2022;36:13115–23. https://doi.org/10.1021/acs.energyfuels.2c02623.
67. International Renewable Energy. Agency (IRENA) and the methanol institute. Innovation outlook: renewable methanol. Abu Dhabi: International Renewable Energy Agency; 2021.
68. International Renewable Energy Agency (IRENA). Renewable power generation costs in 2023. Abu Dhabi; 2024.
69. NREL. Life cycle greenhouse gas emissions from electricity generation: update. Denver; 2021.
70. IRENA and NUPI. Constructing a ranking of critical materials for the global energy transition. Abu Dhabi; 2024.
71. Sendi M, Bui M, Mac Dowell N, Fennell P. Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment. One Earth. 2022;5:1153–64. https://doi.org/10.1016/j.oneear.2022.09.003.
72. An K, Farooqui A, McCoy ST. The impact of climate on solvent-based direct air capture systems. Appl Energy. 2022;325:119895. https://doi.org/10.1016/j.apenergy.2022.119895.
73. Brooks B-GJ, Geissler CH, An K, McCoy ST, Middleton RS, Ogland-Hand JD. The performance of solvent-based direct air capture across Geospatial and Temporal climate regimes. Front Clim. 2024. https://doi.org/10.3389/fclim.2024.1394728.
74. Holmes HE, Realff MJ, Lively RP. Water management and heat integration in direct air capture systems. Nat Chem Eng. 2024;1:208–15. https://doi.org/10.1038/s44286-024-00032-6.

75. Mohan A, Cheng F, Luo H, Greig C, Larson E, Jenkins JD. Direct air capture integration with low-carbon heat: process engineering and power system analysis. Energy Conv Manag. 2024;322:119136. https://doi.org/10.1016/j.enconman.2024.119136.