Design Optimization and Global Impact Assessment of Solar-Thermal Direct Air Carbon Capture

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Abstract

The dual challenge of decarbonizing the economy and meeting rising global energy demand underscores the need for scalable and cost-effective carbon dioxide removal technologies. Direct air capture (DAC) is among the most promising approaches, but its high energy intensity, particularly the thermal energy required for sorbent regeneration, remains a critical barrier to cost reduction and sustainable deployment. This study explores solar-thermal DAC systems that combine concentrated solar thermal technology with low-cost sand-based thermal energy storage to meet this demand. We analyze the techno-economic performance of such systems in both grid-connected and stand-alone configurations. Results show that solar-thermal DAC can achieve annual capacity factors exceeding 80% and CO_2 removal costs as low as \$160–\$200 per ton, making it competitive with leading DAC technologies. An optimal 6000 ton/yr modular system design takes <1 km^2 land-use requirement. The proposed system operates most efficiently with short-cycle sorbents that align with solar availability. The stand-alone Solar-DAC systems, which rely solely on solar energy for both electricity and thermal energy, are particularly promising in regions with high solar capacity and sandy terrain, exhibiting minimal ambient sensitivity from temperature and humidity. In areas with sedimentary basins suitable for CO_2 storage, solar-powered DAC offers a lower-cost alternative to geothermal heating, which often faces geological and economic constraints.

Keywords: Direct air capture (DAC), Solar, Concentrates solar thermal (CST), Sand thermal energy storage, Climate change, Power market, Optimization

1 Introduction

Our society faces the intertwined challenges of climate change and energy demand surge. The year 2024 marked the first year in which global average temperature surpassed the 1.5 °C threshold [1], with rising atmospheric CO_2 concentrations identified as a primary driver of global warming. Simultaneously, the rapid growth of energy-intensive sectors such as data centers, manufacturing, and electrified infrastructure has intensified the search for scalable, low-carbon energy sources. Synthetic fuels have emerged as a promising solution to meet this demand, and CO_2 is a critical feedstock in their production [2]. Direct air capture (DAC) is one of the most scalable approaches to removing CO_2 directly from the atmosphere [3, 4], with the captured CO_2 either permanently sequestered via geological storage or mineralization [5], or utilized to displace fossil-derived carbon in applications such as construction materials [6] and synthetic fuels [7].

Despite recent advancements in DAC system energy efficiency, its significant energy demand is still the major limitation to its scalable and sustainable deployments [8]. DAC operation requires a significant amount of electricity and heat, ranging from 167-305 kWh of electricity and 1.4-3.2 MWh of thermal energy per ton of CO_2 capture, driven by various regeneration temperatures and heating process design [3, 9, 10]. Such extensive energy consumption makes it the largest cost component for DAC's operational expenditure (OPEX), also posing significant risks to its sustainability. While sourcing electricity from the power grid, the DAC system operation inevitably adds scope 2 emission due to fossil generators in the grid generation mixture, which sometimes even lead to net CO_2 emissions instead of net-removal [11, 12].

The thermal energy requirement for solvent/sorbent materials' regeneration poses even higher risks than electricity consumption. Firstly, the regeneration process requires certain temperature targets, typically 100 °C target for solid sorbent DAC systems [13–15] and 800 °C target for liquid solvent processes involving calcination, such as potassium hydroxide (KOH) liquid solvent or calcium hydroxide $Ca(OH)_2$ mineralization [8, 16, 17]. Secondly, the sources of low-carbon heat are often restrictive as thermal energy cannot be easily transferred over long distances [18]. Many studies propose industrial waste heat as an alternative thermal energy source, but it faces challenges such as heat transfer logistics, consistency in availability, and temperature compatibility [9][12]. Current DAC system developers harvest thermal energy either through dedicated low-carbon heat sources such as geothermal energy [19], through electrification process by purchasing verified renewable power [20], or unspecified.

Solar energy provides both clean electricity through photovoltaics (PV) and low-carbon heat via concentrated solar thermal (CST) collectors for DAC systems [21–23]. This study explores the design of solar-thermal DAC systems that utilize solar thermal energy and electricity. We focus on a solid sorbent DAC system with a regeneration temperature of 100 °C, which is within the comfortable range of concentrated solar thermal collectors. The system is complemented with sand thermal storage to improve the operational capacity factor. We evaluate the operation of solar-thermal DAC systems in two scenarios: (1) grid-connection operation representative electricity markets in the U.S.; (2) stand-alone operation powered by PV and battery energy storage, applicable globally. Detailed thermodynamic simulation and operational analyses show that solar-thermal DAC is technically feasible and economically competitive compared to alternative DAC designs while offering reliable and verifiable low-emission carbon removal.

2 Solar-thermal DAC Design and Simulation

We propose a conceptual DAC design that supplies thermal energy through solar heating, addressing the challenges of thermal energy demand and sustainability. The design includes concentrated solar thermal (CST) and sand thermal energy storage to meet the thermal load (see Figure 2). CST converts solar radiation into thermal energy at certain inlet temperatures ranging from 200–500 °C, storing it in sand storage. Excess thermal energy is curtailed when the storage temperature reaches the inlet temperature. During sorbent regeneration, heat is transferred from storage to DAC sorbents, maintained at 100 °C for the required desorption period, after which a water-cooling system cools the DAC system to ambient temperature and initiates a new adsorption cycle. Electricity, needed for both adsorption and desorption processes at varying power levels, can be sourced either from grid interconnections or on-site solar PV plus battery energy storage.

We select a specific MOF [15] as the representative DAC sorbent primarily for its shorter cycle time, which is approximately 1 hour. This enables more flexible DAC operation in response to solar power volatilities. In contrast, typical amine-functionalized sorbents [13] exhibit much longer cycle times from 8 hours up to days, making them less suitable for utilizing the available solar thermal energy efficiently. Secondly, the MOF's rapid cycle time and high energy consumption compared to amine-functionalized sorbents enable rigorous stress testing of our thermodynamic simulation tool and optimization strategy, which are based on very high temporal resolution data.

Thermal energy storage is essential for solar-thermal DAC systems, significantly boosting their capacity factor from below 25–30% (typical of solar-only systems) to over 85% in a cost-effective manner. This study examines sand-based thermal energy storage as an alternative to the more commonly discussed molten salt systems, offering several advantages: lower cost ($4–$10/kWh [24–26] vs. $20–$30/kWh [27, 28]), greater temperature flexibility due to the absence of phase changes[29], and simplified operation without corrosive materials. Additionally, sand is abundant in desert regions—ideal locations for solar-thermal DAC, making deployment more practical despite its lower volumetric energy density.

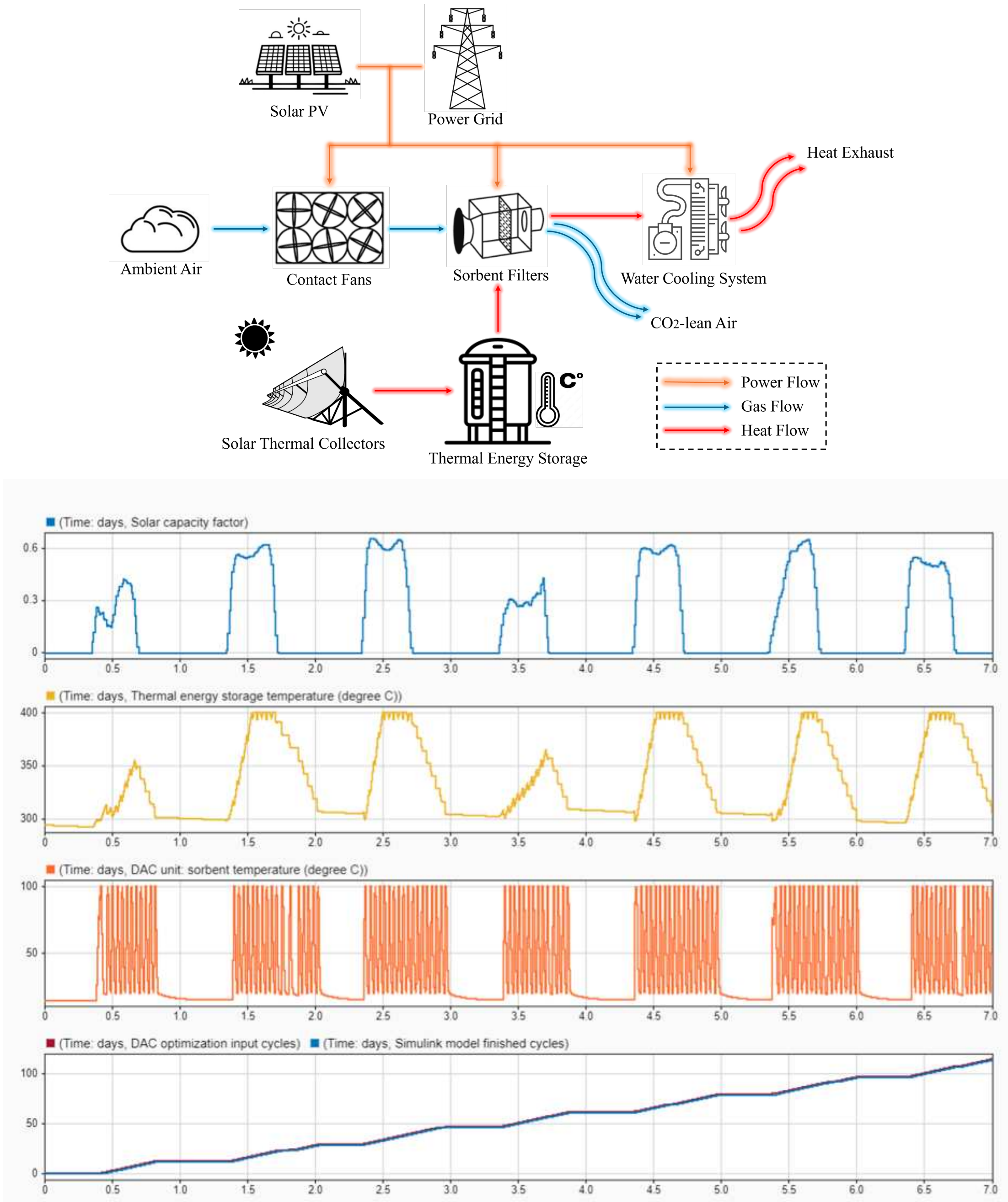

Fig. 1: **solar-thermal DAC schematic and sample week thermodynamic simulation.** The schematic diagram (upper) shows the single unit solid-sorbent DAC system design. A sample week thermodynamic simulation results using MATLAB Simscape (lower) shows the solar capacity factor input (row-1), the sand energy storage temperature profile (row-2), and resulted DAC sorbent temperature cycles (row-3). The optimization used in this study simplifies the simulation thermodynamic assumption, and the DAC regeneration cycle comparison (row-4) show that operation optimization can achieve >99% simulation cycles. This study utilizes a type of MOF [14, 15] sorbent enabling a 1-hour cycle time, minimizing solar curtailment by promptly utilizing thermal energy.

A detailed thermodynamic simulation using MATLAB-Simscape is used as benchmark verification of several critical thermodynamic design properties: (1) minimum thermal source temperature 300 °C for efficient heat exchange to 100 °C regeneration temperature. (2) maximum DAC modular mass/capacity at 6000 ton-CO_2/year, limited by heat transfer coefficient and surface area. This study optimizes the solar-thermal DAC design parameters and tests its performance under grid-connection and stand-alone scenarios with global impact analysis.

3 Design Optimization and Grid-interactive Economics

We examine the design tradeoffs of grid-connected solar-thermal DAC systems. As the CST heating efficiency decreases with higher required temperature [30, 31], the trade-off between the inlet target temperature, storage capacity, and solar thermal heating capacity leads to an optimal design space (see Figure 2). While increasing the solar concentration ratio can increase solar efficiency at a given temperature, it disproportionally increases the unit CAPEX compared to just adding CST capacity directly. Both CST and DAC systems exhibit scaling benefits, but the heat transfer coefficient imposes an upper limit on size. For consistency, we define a modular DAC system with a 6000 ton-CO_2/year capacity as the baseline, based on simulation results, and use it as the benchmark for further analysis. This modular design requires approximately 0.43 km^2 of land for solar PV and CST equipment, based on typical U.S. land-use requirements[32], so the entire facility should occupy no more than 1 km^2 of land.

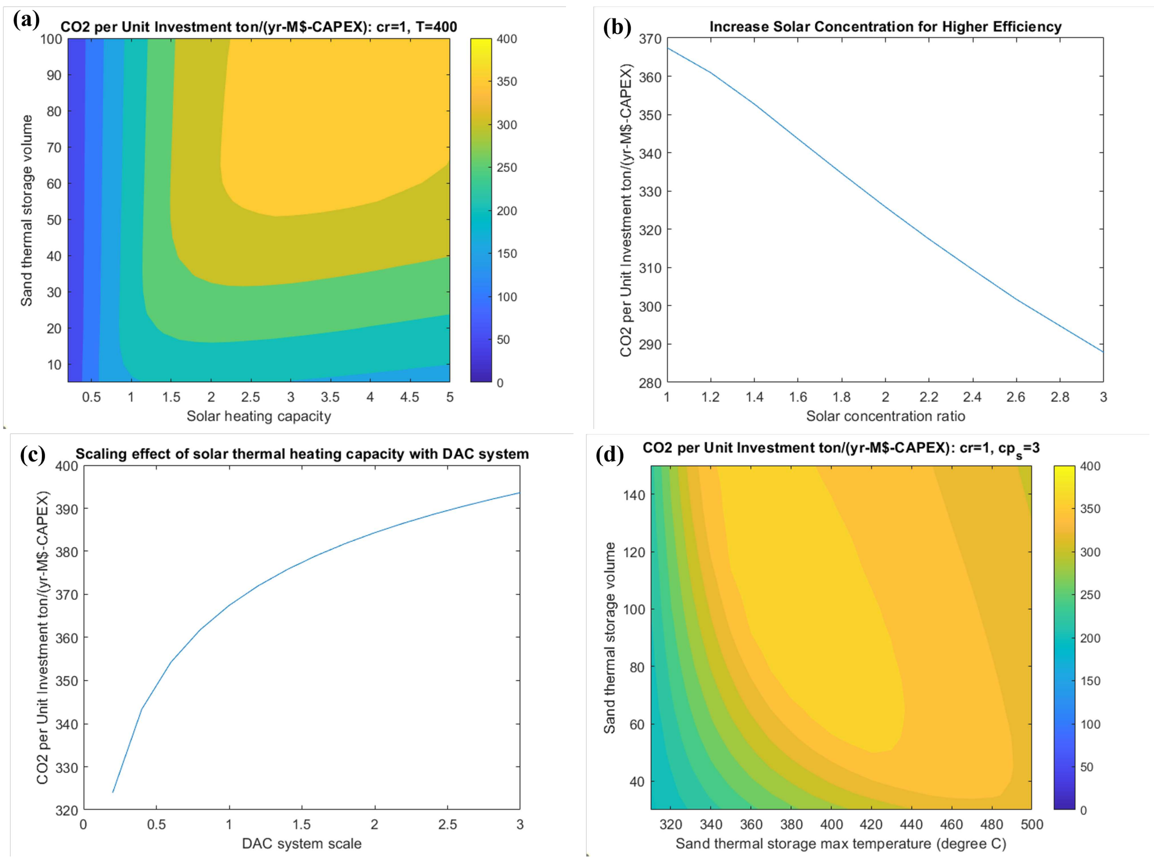

Fig. 2: **solar-thermal DAC design parameter optimization using TX power market connection as example.** (a) optimal CST heating capacity vs sand storage capacity; (b) impact of solar concentration ratio for net-CO_2 abatement per unit CAPEX; (c) scaling effect of DAC and CST CAPEX, unit 1 = 6000 ton-CO_2/year capacity; (d) optimal sand storage max temperature vs sand storage capacity, higher max temperature meaning higher usable heat for the same storage capacity, but lower solar heating efficiency for CST. Incentive selling price = \$200/ton-CO_2, which is sufficiently high to support nearly 100% operational capacity factor. Eventual optimal design parameters for 6000 ton-CO_2/year modular solar-thermal DAC: CST heating capacity = 3 MWh/5min, sand storage capacity = 70 MWh/100°C operation range, sand storage max temperature = 400 °C, no additional solar concentration. When capacity factor of solar-thermal DAC is sufficiently high (>80%), this optimal design settings are very robust across different power markets and stand-alone solar PV powered systems.

We consider western Texas as the representative deployment site for its abundant solar energy and the extensive sedimentary basin for CO_2 storage, where the largest commercial DAC project is currently being developed [33]. The optimal levelized cost of CO_2 ($LCCO_2$) achieves \$220/ton with optimized system design and operation, considering the wholesale electricity price volatility of the Texas grid. The levelized cost decomposition is as follows: DAC system CAPEX 43%, sorbent materials cost and O&M 18%, electricity 16%, thermal energy from solar 23%.

However, grid-connection scenarios also present risks. Notably, although electricity accounts for just 19% of total energy consumption (with thermal energy making up the remaining 81%) in the representative DAC technology, its cost is nearly equivalent to that of thermal energy. This is especially concerning given the steady rise in average electricity prices across the U.S. over the past decade and increased volatility driven by higher renewable penetration [34]. Moreover, consumers also incur additional fixed charges and peak demand charges that may take around 30% of the electricity cost [35]. In addition, the interconnection queueing process has emerged as a major bottleneck amid growing electricity demand from electrification and data center expansion. As of 2023, the median interconnection wait time reached five years [36], with growing uncertainty as the grid undergoes a rapid transition..

4 Stand-alone Solar-DAC System and Global Impact

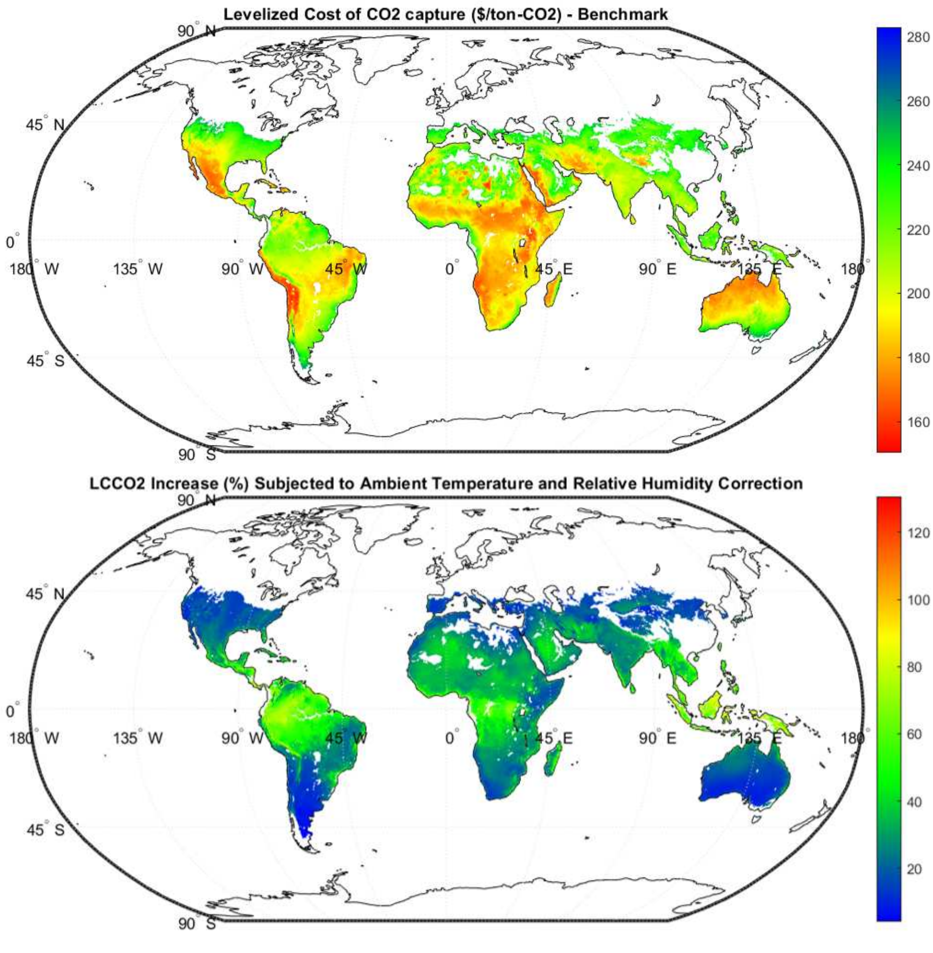

Fig. 3: **Stand-alone Solar-DAC System (power+thermal) global deployment cost analysis and potential ambient sensitivity using presentative sorbent technology.** (upper) global mapping of solar stand-alone $LCCO_2$. The analysis focuses on regions with solar capacity factor >15% with 107713 points globally, some places without calibrated data, such as the Sahara desert, are excluded. (lower) ambient sensitivity to local temperature and relative humidity of a representative sorbent material. The sample sorbent is particularly sensitive to relative humidity, which significantly increases costs in humid tropical regions. In contrast, sandy terrains with lower humidity levels offer more favorable operating conditions for this DAC technology.

We analyze a stand-alone solar-DAC system that relies solely on on-site photovoltaics (PV) and battery storage for electricity, eliminating the need for grid connections. This setup improves flexibility for rural deployment and avoids long interconnection delays. Figure 3 shows the global $LCCO_2$ results, where a similar design optimization framework to the grid-connected case study has been applied to achieve the minimal $LCCO_2$. A pre-optimized 6000 ton-CO_2/year capacity modular stand-alone solar-DAC system design is used for deployment analysis, where the DAC power source is solar PV and battery energy storage. The levelized cost of CO_2 ($LCCO_2$) in ideal regions ranges from \$160-\$200/ton-CO_2. In western Texas and California specifically, stand-alone solar-DRC systems are \$10-\$20 cheaper than grid-connection using wholesale electricity price in 2022, before factoring in grid interconnection charges.

Stand-alone solar-DAC systems can have out-sized impacts of <\$180/ton-CO_2 cost in most regions with good solar radiation, especially (1) Gulf of California coastal to West Texas region; (2) Atacama Desert Solar Corridor in North Chile and Peru; (3) Red Sea coastal to Persian Gulf regions; (4) Sub-Saharan Africa; (5) North Australia. Except for parts of Sub-Saharan Africa, these regions are largely covered in sandy terrain and are already recognized as emerging solar energy hubs. This aligns well with the proposed sand-based thermal energy storage, while the arid, low-density landscapes help reduce land and infrastructure costs. Moreover, the solid sorbent technology does not require process water and potentially capture water vapors during operation [37, 38], making it suitable for deployment with recycled or alternative cooling methods and minimal water demand.

Based on 1 km^2 land-use for the modular system, 1 Gt/year abatement capacity takes about 208,000 km^2. This is 30% of total area of Texas or 15% of the Great Australian Desert. The stand-alone solar-DAC systems deployed in sandy terrain alone could exceed global total potential capacity of 26.9 Gt/year, mostly in (1) Arabian Desert, 11.2 Gt/year; (2) Great Australian Desert, 6.6 Gt/year; (2) Kalahari Desert in Southern Africa, 4.3 Gt/year.

A research gap in solar-DAC system deployment globally is the atmospheric sensitivity to ambient temperature and relative humidity, which significantly affects energy consumption and CO_2 capture capacity[39, 40]. For example, our representative MOF sorbent and other solid sorbents (including amine-functionalized sorbents) selectively bind CO_2 but also capture water vapor at high humidity, reducing its efficiency. In contrast, liquid solvents using calcium hydroxide $Ca(OH)_2$ benefit from elevated humidity and temperature to enhance CO_2 adsorption. Our global analysis of the potential increase in $LCCO_2$ globally for the representative sorbent technology Figure 3(b) show that the ambient sensitivity corrections is minimal in most sandy terrains identified as suitable for stand-alone solar-DAC system (<20%). We demonstrate that robust DAC sorbent technology is already available for optimal solar-DAC deployment in ideal landscapes. However, in environments that deviate significantly from laboratory conditions, such as near-equatorial and rainforest regions, the worst-case scenario could double the costs, highlighting the need for further research into more resilient sorbents.

5 Comparative Cost Analysis with Geothermal

We conduct a comparative analysis between stand-alone DAC systems using solar and geothermal energy to highlight the cost-effectiveness of the solar approach. Geothermal energy has been the exclusive choice for low-carbon heat in existing commercial DAC projects. Using geothermal LCOE data [41] from the United States, we calculate the $LCCO_2$ for a stand-alone DAC system employing the same sorbent technology, under the assumption that all energy consumption is met by geothermal. Figure 4 illustrates the differences in $LCCO_2$ between the two systems, where more negative values indicate a cost advantage for the solar-DAC system.

DAC systems using geothermal energy show comparable $LCCO_2$ with solar energy in most regions, typically around \$160-\$210/ton-CO_2. For instance, in the southwestern U.S., geothermal reservoirs exceeding 300°C at 5-7 km depth can achieve LCOE ranges between \$30-\$70/MWh [41]. However, regional differences are significant: solar energy is more cost-effective in West Texas due to high solar potential and costly geothermal extraction, while the Pacific Northwest favors geothermal energy due to lower solar availability. The cause of high geothermal LCOE in West Texas is sedimentary Permian basin geology with low geothermal temperature gradients and limited permeability, making high-temperature extraction difficult and expensive [42]. Sedimentary basins, suitable for geological CO_2 storage, can only harvest geothermal energy in relatively low temperatures (100 to 200°C) [43]. Even in regions with both geothermal potential and basaltic CO_2 storage options, drilling must be spaced carefully to avoid conflicts [44].

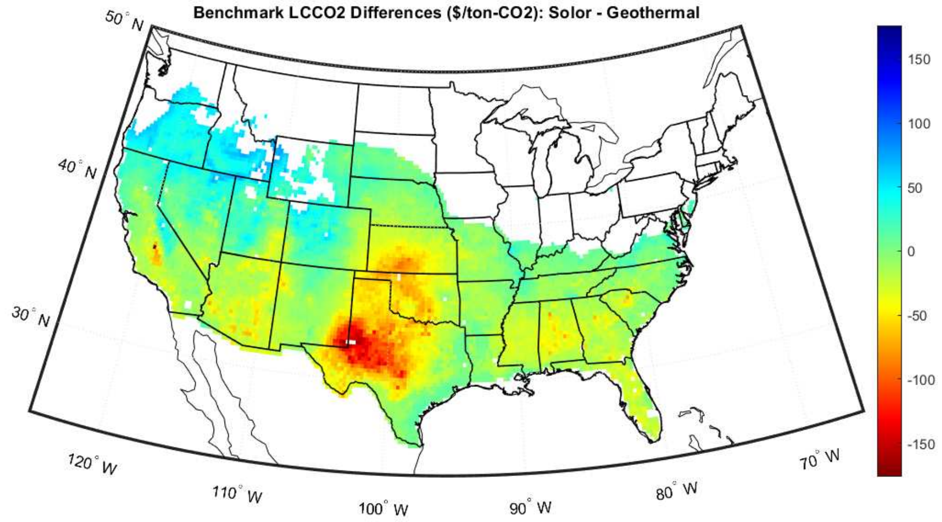

Fig. 4: **Stand-alone Solar-DAC and Geothermal-DAC system comparison in the continental U.S. region.** Comparing the $LCCO_2$ of stand-alone solar-DAC and stand-alone geothermal-DAC by mapping their differences (solar subtracting geothermal). Negative value shown in red color indicating in favor of solar deployment in the West Texas regions.

Our comparative case study in the United States reveals a potential conflict between geothermal energy costs and geological CO_2 storage potential. For cost-effective DAC systems, proximity to verified geological storage is essential. Yet, many identified solar-rich regions, such as the Atacama Desert Solar Corridor, Red Sea coasts, and Sub-Saharan Africa, lack positively confirmed CO_2 storage capacity. In contrast, regions like West Texas, South Africa, and the Xinjiang Tarim Basin offer both verified sequestration [45, 46] and competitive costs (around \$200/ton-CO_2) for solar-DAC system, presenting near-term opportunities. In these regions, the requirements for efficient geothermal reservoirs, including high-temperature gradient and permeable formations that facilitate water circulation, cannot be met as they conflict with trapping CO_2 in the supercritical phase under the cap-rock sealing layers. This potential conflict positions stand-alone solar-DAC systems as a promising alternative in sedimentary basins, with sites like the Permian Basin (USA), the Great Artesian Basin (Australia), and the Neuquén Basin (Argentina) combining abundant solar potential, ample geological storage, and favorable terrain without competing with costly geothermal drilling.

6 Discussion

This paper simulated and optimized concentrated solar thermal (CST) coupled with sand thermal energy storage design to supply low-carbon heat for DAC systems. The tested DAC system uses solid-sorbent materials with a regeneration temperature of 100°C and approximately 1 hour per cycle of adsorption-desorption operation. Both grid-connection scenarios and stand-alone scenarios show a levelized cost of CO_2 ($LCCO_2$) around \$200/ton-CO_2 with solar capacity factor >20%, competitive with existing techno-economic analysis reported in the literature. It demonstrates that an optimized solar-thermal DAC system can operate at >80% capacity factor annually and almost constantly through solar-abundant seasons, making solar thermal energy a feasible and ideal source of low-carbon heat for global large-scale DAC deployment.

Our analysis shows that the stand-alone solar-DAC system demonstrates cost-effectiveness comparable to grid-connected systems while offering several key advantages, including deployment flexibility without interconnection requirements, and insulation from electricity price risks amid anticipated demand surges driven by global electrification and data center expansion. The stand-alone solar-DAC system has the potential to make a significant global impact, with numerous suitable deployment areas. These regions are often characterized by sandy terrains in arid zones, where land and sand-based energy storage costs are minimal. The representative sorbent's sensitivity to ambient temperature and relative humidity is well-suited for such environments. However, deploying the system in lower latitudes, such as near the equator or rainforest areas, would require different types of sorbents with enhanced tolerance to higher temperatures and humidity, which can be an important future research topic.

The solar-DAC system avoids potential geothermal compatibility issues and drilling activity conflicts while addressing local CO_2 geological storage limitations. They are particularly well suited for sedimentary basins with sandy terrains, as exemplified by West Texas in the U.S., which is currently being developed as a carbon capture and storage hub. In these areas, solar energy not only provides a competitive option for powering DAC systems but is likely the optimal choice. Moreover, the use of mature solar generation technologies like CST and PV reduces overall project risk, particularly given the emerging state of carbon sequestration markets, as these assets can be repurposed for other business applications if necessary.

The solar-thermal DAC system shifts the thermal energy and electricity cost from continuous operational expenditure (OPEX) to capital expenditure (CAPEX). The majority of the remaining OPEX is associated with sorbent material costs. This transition makes the DAC system more capital-intensive and, consequently, more sensitive to financial assumptions and policy changes, particularly the incentive per ton of CO_2 removal. To ensure the success of solar-thermal DAC systems, low-cost green financing, and long-term stable policy support will be more critical than achieving purely engineering optimality.

7 Methods

7.1 Overview

Our analysis is generally categorized into three parts. First, system conceptualization and simulation using MATLAB Simulink + Simscape. Second, DAC + solar thermal system design parameter and grid-interactive operation optimization. Third, using the pre-determined system design for global stand-alone solar-DAC system performance simulation, including sensitivity to ambient temperature and relative humidity. All simulation incorporate one year data (2022 sample year data with 5-min resolution for grid-connection study, 1-hour resolution for stand-alone global study) to support analysis for both daily and season patterns. For sustainability comparison, "CO_2 capture efficiency" is defined as below. For example, 80% CO_2 capture efficiency means 0.2 ton of CO_2 is emitted to capture 1 ton of CO_2 through DAC system.

$$\eta_{CO_2} = \frac{CO_2^{net}}{CO_2^{captured}} = 1 - \frac{CO_2^{emit}}{CO_2^{captured}} \tag{1}$$

The levelized cost of CO_2 ($LCCO_2$) evaluated in this study incorporates both capital expenditures (CAPEX) and operational expenditures (OPEX). The CAPEX component encompasses equipment costs associated with initial investments, specifically including direct air capture (DAC) systems, solar-thermal concentrating systems (CST) paired with thermal energy storage, and photovoltaic (PV) solar installations integrated with battery energy storage. The OPEX component comprises energy expenditures and sorbent material costs (e.g., sorbent degradation), inclusive of operation and maintenance (O&M) expenses. For stand-alone system analyses, energy-related OPEX is eliminated, with all energy infrastructure costs consolidated into the CAPEX framework. Costs associated with land acquisition, labor, and auxiliary infrastructure are excluded from the scope of this assessment.

It is acknowledged that this methodological approach aligns the $LCCO_2$ boundary conditions with standard techno-economic analysis (TEA) conventions, facilitating direct comparison with prior literature. However, the exclusion of ancillary real-world expenditures—such as infrastructure, permitting, labor, and site preparation—may result in conservative cost estimates relative to full-scale commercial implementations. This simplification underscores the analytical focus on technology-centric cost drivers while recognizing potential deviations from comprehensive industrial cost structures.

7.2 Simulation and Optimization

To conceptualize the design of a solar-thermal energy system using Concentrated Solar Thermal (CST) technology, we first understand how solar radiation is converted into usable heat. Based on existing research, the efficiency of this conversion depends on three key factors [30, 31]: (1) Sunlight intensity: measured by the solar radiation available at given time; (2) Target temperature: How hot the system needs to get that guarantee other subsystem performance, such as thermal energy storage and heat transfer efficiency; (3) Solar concentration ratio: How much solar radiation is focused onto the system (area of mirrors or lenses). These factors affect the eventual solar thermal efficiency: higher target temperatures reduce efficiency and more solar radiation or a higher concentration ratio improves efficiency. We combined existing research data with basic physics principles to create a semi-physics inspired function that links efficiency to these three factors, where solar radiation is a known input provided by solar time series data. Target temperature and concentration ratio are design parameters to be optimized during the system's optimization to balance performance and cost. The solar-thermal collector efficiency is given by the function in form of:

$$\eta_{c_t}(DNI_t, cr, T) = 0.78 - \eta_{loss} = 0.78 - \alpha T^2 \cdot \frac{\beta}{DNI_t + m} \cdot \frac{\gamma}{cr} \tag{2}$$

where the DNI_t is direct normal irradiance data for solar time series, cr is the solar concentration ratio and T is the target temperature given in °C. The efficiency η_{c_t} equals a baseline highest efficiency (0.78) minus losses η_{loss}. Other parameters are obtained by fitting this equation to experimental data reported in literature.

Given the efficiency, the total amount of solar-thermal flux is given by:

$$s_t = DNI_t * cp * \eta_{c_t} \tag{3}$$

where cp is the solar-thermal capacity, which measures the sizing of CST equipment.

A simulation model using MATLAB Simulink (signal package) + Simscape (thermdynamics and fluid mechanics package) was developed to simulate the thermodynamics behaviors that are sensitive to target temperature settings. The simulation model consists of several subsystems: (1) solar thermal source and storage subsystem; (2) DAC thermal subsystem; (3) water cooling subsystem; (4) sensor and control subsystem. The simulation model is parameterized and connected to the DAC operation optimization code. It receives signal as simulation input such as design parameters (e.g., target temperature) and control signals (e.g., when to initiate regeneration cycle which transfer heat from thermal storage to DAC thermal system). The DAC operation optimization framework not only streamlines high-fidelity thermodynamic simulations but also incorporates strategic operational scheduling to dynamically respond to volatile electricity prices, thereby aligning DAC energy consumption with cost-minimizing grid interactions. The optimization objective function maximizes the total profit of the DAC operation.

$$max \sum_t \pi d_t - \lambda_t C_t(P^a u_t + P^d v_t) - S z_t \tag{4}$$

where πd_t is the total revenue by captured/desorbed CO_2 d_t multiplied by incentive π, minus the cost of power consumption $\lambda_t(P^a u_t + P^d v_t)$, real-time price λ_t times power consumption for adsorption and desorption $P^a \& P^d$ times binary activation status $u_t \& v_t$, minus the cycle switching cost $S z_t$. CAPEX component is a fixed cost which is a constant for optimization for any given horizon, therefore does not affect the operational variables. The final $LCCO_2$ will be corrected by adding the CAPEX. Similar to power system optimization, this operational optimization does NOT guarantee recovery of all costs for DAC system.

While the simulation model employs sub-second temporal resolution for thermodynamic precision, the optimization framework adopts a 5-minute sampling interval—synchronized with wholesale electricity price fluctuations—to enable real-time decision-making. This dual approach ensures computational tractability (7–10 seconds for a full-year optimization, a 300–500× speed improvement over conventional 45–60 minute thermodynamic simulations) while preserving >99% solution quality (<1% operational cycles deemed infeasible in simulation validation). Crucially, the model advances beyond simplification by integrating grid connectivity constraints and price-driven operational strategies, ensuring DAC systems function as responsive, grid-aware assets rather than isolated thermodynamic processes. More details about the simulation settings and full optimization problem formulation set up see Supplementary information.

7.3 Stand-alone and Global Analysis

System Configuration and Global Analysis Methodology. For the stand-alone solar-DAC system evaluated in this global analysis, system parameters—including the sizing of solar photovoltaic (PV) arrays, battery energy storage systems, solar thermal collectors, and sand-based thermal storage—were first optimized using a representative location (Texas, USA). These parameters were then applied uniformly across all global locations. While this approach ensures methodological consistency, the authors recognize that it may yield sub-optimal configurations, as site-specific solar profiles were not incorporated into individual optimizations. Consequently, the reported levelized cost of CO_2 ($LCCO_2$) represents an upper bound, with potential for reduction through location-specific parameter tuning.

Impact of Ambient Environmental Conditions. The global analysis evaluates the influence of ambient temperature and relative humidity on two critical performance metrics of DAC systems: (1) energy efficiency and (2) CO_2 capture rate. Hourly gridded global ground-level temperature and relative humidity data were used to calculate location-specific correction factors. These factors normalize energy efficiency and CO_2 capture rates relative to standard laboratory conditions (20°C, 50% RH). Deviations from these optimal conditions typically reduce both metrics, though regional variability exists. The electricity consumption correction after numerical fitting is given by the following, using quadratic equation for temperature T fitting and exponential function for skewed symmetric behavior of relative humidity RH:

$$C_t = [1.9 + 0.01(T - 20)](RH - 0.4)^2 e^{RH-0.4} + [1.5 + 0.003(T - 20)^2] \quad (5)$$

The capture rate or abatement correction similarly:

$$\eta_t = 65 - 0.01T^2 - (T + 20)(RH - 0.4)^2 \quad (6)$$

Cost Implications and Methodological Constraints. To quantify the $LCCO_2$ impact of ambient conditions, operational optimization was re-executed using adjusted hourly energy consumption and CO_2 capture rates derived from environmental data. However, this secondary optimization retained the original system sizing parameters, potentially compounding sub-optimality. As a result, the estimated cost penalty from ambient conditions may be conservatively high. Future work could mitigate this limitation through integrated design optimization that simultaneously accounts for local climate variability and component sizing.

8 Data and Code Availability

All data, code, and MATLAB Simscape Simulation models used in this study are available and can be directly accessed in the following Github Repository.

9 Declaration of Interests

The authors declare no competing interests.

10 Acknowledgments

To be finalized upon final decision.

11 Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT 4.0 only in order to improve readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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