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Meeting Net-Zero America Direct Air Capture Targets with Sedimentary Basin Geothermal Heat While Considering Environmental Justice

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ABSTRACT

We investigate the potential of using sedimentary basin geothermal heat to drive solid-sorbent direct air capture (DAC) geospatially across the contiguous United States. DAC facilities are machines built for the purpose of removing CO_2 from the air and require substantial amounts of heat. Sedimentary basin geothermal resources may be well positioned to provide this thermal energy because they are ubiquitous, do not require novel drilling technologies, have sufficient temperature to drive solid-sorbent DAC, and have not already been included in energy transition pathways. Here, we find that sedimentary basin geothermal resources could support almost 5 $GtCO_2$/yr of CO_2 removal capacity across the United States, which is an order of magnitude more DAC capacity than suggested needed for a 2050 net-zero economy. There are multiple locations with sedimentary basin heat amenable for solid-sorbent DAC that are not typically considered for geothermal development (e.g., Louisiana, South Dakota). As the thermal energy demand of the solid-sorbent DAC system modeled in this study generally decreases with decreasing air temperature or relative humidity, the locations with the highest CO_2 removal potential are those with both thermal energy resources and with lower air temperature and relative humidity. We also consider the location of disadvantaged communities within our analysis because energy development has not occurred equitably and the Justice40 initiative requires 40% of the benefits from federal investments in climate and clean energy go to disadvantaged communities. We find ~0.9 $GtCO_2$/yr (~18%) and ~4 $GtCO_2$/yr (~82%) of the total ~5 $GtCO_2$/yr of CO_2 removal capacity is located within, and outside of, disadvantaged communities, respectively. Overall, our study demonstrates that sedimentary basins could provide value to justice-centered pathways that meet mid-century energy transition goals by supporting DAC deployment.

1. INTRODUCTION

Sedimentary basins are naturally porous and permeable geologic formations and at least one, if not multiple, sedimentary basins underly approximately half the United States (USGS 2022). These deep (i.e., 1 to 5 km) geologic formations are naturally full of geothermally-heated brine, but prior work has found the temperature of this brine to be too low (i.e., 100-150°C) to support electricity generation (Porro et al. 2012). While there is substantial demand for thermal energy at temperatures less than 150°C (Fox, Sutter, and Tester 2011), drilling wells to access deep heat is costly and, historically, electricity was the only commodity valuable enough to warrant this expense. As such, the potential that sedimentary basins for geothermal development is generally understudied compared to other geothermal energy resources (i.e., hydrothermal, EGS).

While developing 1-to-5 km deep geothermal resources has been focused on electricity generation, recent work has discussed the importance of, and potential for, increasing the capacity of geothermal systems that provide heat, not electricity, via drilling wells (Tester et al. 2021; Beckers et al. 2021; USDOE 2019). Within the geothermal field of study, this area has been named "deep direct-use" because much of the commercial direct-use (i.e., heat, not electricity) systems in the United States use geothermal resources available at the surface (e.g., hot springs) or that that are accessible with shallow wells (Beckers et al. 2021). This recent interest in deep-direct use suggests that, in the future, drilling deep wells to supply carbon-neutral heat could provide value to decarbonization efforts.

One such emerging decarbonization effort is deploying Direct Air Capture (DAC), which is an approach to carbon dioxide removal (CDR). CDR is important to decarbonization pathways, as it may be less expensive to transition to net-zero carbon economies instead of zero carbon economies due to some technologies, processes, or sectors that are "hard to decarbonize" (Davis et al. 2018). As such, CDR approaches, like DAC, may be necessary to offset these residual "hard to decarbonize" emissions (EPRI and GTI Energy 2022; Larson et al. 2020).

DAC facilities are machines built for the purpose of providing CDR and do this by a) absorbing atmospheric CO_2 into a solvent or solid material; b) using electricity and heat to detach the absorbed CO_2; and then c) compressing the captured CO_2 so it can be permanently stored in the subsurface. Across these steps, and particularly the second step, DAC is very energy intensive. For example, given the deployment levels of DAC required to achieve climate targets and current energy efficiencies, prior work has found that DAC alone in 2100 may require as much as half the total global energy consumed in 2016 (Realmonte et al. 2019). While the energy requirements vary with specific technologies, a general rule-of-thumb is that ~80% of the energy demands for DAC is thermal, with the remaining 20% being electrical.

Solid-sorbent systems are a prominent approach to DAC and there are many reasons why geothermal resources are beneficial sources of thermal energy for these DAC systems. For one, solid-sorbent systems require thermal energy at relatively low temperatures (~100°C), which can be achieved using geothermal resources. Second, given their high capital cost, prior work has shown it is optimal for DAC to provide as much CDR as possible, thus be paired with energy sources that are continuously available, like geothermal (Breyer, Fasihi, and Aghahosseini 2020; Bistline and Blanford 2021; Hanna et al. 2021). Third, it is important that low-carbon energy be used to drive DAC because the net carbon removal is sensitive to the carbon footprint of energy (Terlouw et al. 2021; Hanna et al. 2021).

While past work has investigated using geothermal energy to drive solid-sorbent DAC (Pett-ridge et al. 2023; McQueen et al. 2020), very little work has investigated using sedimentary basin geothermal resources specifically. There are multiple interrelated reasons why sedimentary basin geothermal resources may be well suited to this application. First, the temperature range of sedimentary basins heat (i.e., 100°C to 150°C (Porro et al. 2012)) aligns with what is needed to drive solid-sorbent DAC. Second, sedimentary basins are ubiquitous and can be accessed with existing drilling technology. In contrast, new exploration technologies are needed to discover more hydrothermal resources and new drilling technologies are required to deploy EGS resources (USDOE 2019). Third, because sedimentary basins are understudied, this energy resource has not already been included in energy transition pathways. As stated in prior work, it is important to be cognizant of potential competing uses for low-carbon energy so that deploying DAC does not hinder other decarbonization efforts, for example of the electricity system (Pett-ridge et al. 2023).

In this study, we present a geospatial screening analysis quantifying the potential that sedimentary basin geothermal resources may have for solid-sorbent DAC deployment. This is novel for multiple reasons. First, while our prior work has investigated a case-study analysis of using brine from sedimentary basins for DAC (Adams et al. 2020), this is the first study we are aware of that studies this potential geospatially. Second, we also consider as part of this geospatial analysis the location of disadvantaged communities. Historic and ongoing energy development has not occurred equitably (Cranmer et al. 2023), and in response, the Justice40 initiative requires that 40 percent of the benefits from federal investments in climate and clean energy go to disadvantaged communities (The White House 2021). Including the location of disadvantaged communities within this study represents an important and necessary paradigm shift to justice-centered and equitable deployment of climate solutions.

2. METHODS

Our methodology consists of three tasks:

1. First, we estimated the deep direct-use potential of sedimentary basin geothermal resources across the United States by a) modifying the generalizable GEOthermal techno-economic simulator (genGEO) and then b) applying genGEO results across a geospatial dataset of sedimentary basin properties. More information about this task is provided in Section 2.1.
2. Second, we estimate the thermal energy required by DAC as a function of weather and couple these results to the total potential for sedimentary basin geothermal (from step 1) to estimate the total CO_2 removal capacity for solid-sorbent DAC using sedimentary basin geothermal heat. More details of this task are provided in Section 2.2.
3. Lastly, to consider environmental justice, we estimate the portion of this potential CO_2 removal capacity that is co-located with, and without, disadvantaged communities. We compare these estimates to the estimated capacities suggested to be required within the energy transition literature. This part of our analysis is described more in Section 2.3.

2.1 Sedimentary Basin Geothermal Potential Estimate

Our prior work developed genGEO to estimate the electricity generation potential and cost of geothermal power plants using coupled reservoir-well-power cycle models (Adams et al. 2021). When brine (water) is used as the subsurface heat extraction fluid, the implemented power cycle model in genGEO is an Organic Rankine Cycle (ORC): based on the input geologic conditions (i.e., reservoir depth, transmissivity, and temperature gradient), genGEO can optimize the geofluid production flowrate to minimize the cost of electricity generation from the ORC. Here, we modify this default genGEO model by removing every component of the ORC except the geofluid-to-working fluid heat exchanger. As such, this direct-use version of genGEO is a coupled reservoir-well-heat exchanger loop that optimizes the geofluid flowrate and to minimize the levelized cost of heat (LCOH), depending on the reservoir properties (i.e., reservoir depth, transmissivity, and temperature gradient).

Removing all components from the ORC except the heat exchanger introduces another degree of freedom into the modeled system and thus requires making additional assumptions, which we use Figure 1 to explain. Given that in practice, the process that uses the heat (i.e., DAC) would remove that additional degree of freedom, we made our assumptions as conservatively as possible.

Figure 1: Generic Heat Exchanger Example. T_{well} is the temperature of the produced water at the wellhead; T_Y is the temperature of the water after the heat has been transferred to the secondary fluid and prior to being re-injected into the subsurface; T_{IN} is the temperature of the secondary working fluid prior to being heated from the produced water; T_{need} is temperature of the secondary working fluid after being heated from the produced water.

T_{well} is a function of the properties of the subsurface (e.g., depth), thus no additional assumptions are made regarding this temperature within genGEO. T_{need} is a function of the process that is using the heat and, here, we assume T_{need} is 5°C less than T_{well}. Similarly to T_{need}, T_{IN} will also be constrained and optimized by the process that uses the heat. Here, we assume that T_{IN} is 20°C because it will likely be brought down to ~5°C above ambient conditions and assuming an ambient temperature of 15°C is common for geothermal studies (Adams et al., 2021, 2015). Lastly, to determine T_Y, we implement an additional optimization into genGEO. By default, genGEO can optimize for the production mass flowrate that minimizes cost, but this cost is also influenced by T_Y. If T_Y equals T_{well}, then no heat transfer occurs and the LCOH is thus infinitely large. At the other extreme, the most heat transfer possible occurs if T_Y equals T_{IN}, which in turn results in a large LCOH because a very large heat exchanger is required. Thus, we determine T_Y by setting T_Y equal to $T_{IN}+\delta$ and increasing δ until the minimum LCOH is found. This requires implementing a double iteration when solving genGEO: the mass flowrate that minimizes LCOH for a given δ is found while δ is increased until the minimum LCOH is found.

We use this direct-use version of genGEO to estimate the geothermal heat required for DAC in three steps:

1. We use the direct-use version of genGEO to estimate the LCOH from sedimentary basin geothermal resources across the same parameter space of reservoir transmissivities, geothermal temperature gradients, and depths as we did for electricity generation in our prior work (Adams et al. 2021). The outcome of this is a database of needed temperatures, thermal energy, and LCOH across a large combination of geologic conditions.
2. We use resulting temperatures from step 1 to find the heat available for solid-sorbent DAC specifically. Using process-level assumptions from prior work estimating the potential of geothermal heat for DAC, we assumed that T_{need} must be at least 100°C and T_Y is 70°C (McQueen et al. 2020). These two design temperatures were implemented into the database from step 1 using percentages. For example, if in a given combination of geologic conditions, 100 MW_{th} was available and the T_{need} was 100°C, we assume that only 37.5 MW_{th} is available for DAC because the 100 MW_{th} was estimated assuming that the geothermal heat can be taken down to 20°C, as previously described. The outcome of this step is a database of thermal energy available to DAC across a large combination of geologic conditions.
3. We follow the same approach established in our prior work and use this large parameter-space of results as a look-up table to estimate the geospatially-distributed quantity of heat available from sedimentary basin geothermal resources across the United States (Ogland-Hand et al. 2022). In our prior study, we applied electricity generation results to geologic data across a multi-state region of the United States. Here, we apply the generalized heat results from step 2 across the entire contiguous United States using the geologic database from the Sequestration of CO_2 Tool (SCO_2T^{PRO}) that covers the contiguous United States with a 10 km x 10km resolution (Ogland-Hand et al. 2023). The outcome of this step is spatially explicit map of the thermal energy available for solid-sorbent DAC on a 10 km x 10 km resolution.

2.2 Geospatial Estimate of the Thermal Energy Required by Direct Air Capture

The thermal energy required to drive DAC is a function of many factors and in this study, we only consider air temperature and relative humidity. We estimate the thermal energy requirements as a function of air temperature and humidity using process-level modeling results extracted and adapted from prior work (Sendi et al. 2022). Specifically, Sendi et al. (2022) finds three thermal energy loads for solid-sorbent DAC: a) heating the sorbent bed; b) pre-heating water; and c) generating steam to purge the sorbent bed. They find the thermal loads of preheating steam can be met using the heat of CO_2 compression that occurs on site after the CO_2 is desorbed. As such, the thermal energy required to heat the sorbent bed and to generate steam are the only thermal loads that may need to be met with sedimentary basin geothermal heat. We use data provided by Sendi et al. (2022) to create a response surface model of the thermal energy required for both these loads as a function of air temperature and relative humidity. We then couple those equations with hourly weather data from our prior work to estimate the thermal energy loads of solid sorbent DAC across the United States (Brooks et al. 2024). Our prior study used hourly temperature and relative humidity data for the years 2000 through 2019 from the ERA5-Land dataset (Munoz Sabater 2019), post-processed by the European Centre for Medium-Range Weather Forecasts. Across the temporal (i.e., 2000-2019) and spatial boundaries (CONUS) of the study, this hourly weather dataset includes about 12 billion datapoints. For this analysis, we use temporally averaged hourly data for the entire twenty-year period.

2.3 Considering Environmental Justice

We use the Energy category from the Climate and Economic Justice Screening Tool to define the location of disadvantaged communities (USA Council on Environmental Quality 2024). This tool uses datasets as indicators of burdens, organized into different eight different categories across 2010 census tracts. Using this tool and the Energy category, communities are defined as disadvantaged if they are a) at or above the 90^{th} percentile for energy cost or PM2.5 in the air, and b) are at or above the 65^{th} percentile for low income.

We selected the Energy category for this study given its potential relevancy to DAC siting. As DAC is very energy intensive, it could be argued that DAC should be developed outside these disadvantaged communities so that the existing energy burden is not further exacerbated. Alternatively, if DAC has the potential to remove PM2.5 in the air, in addition to CO_2, it could also be argued that DAC could bring additional co-benefits to these disadvantaged communities. To address this critical trade-off, for this study, we provide the quantity of CO_2 removal potential (calculated as described in Section 2.2) that occurs in disadvantaged communities and outside of disadvantaged communities, as defined from the Energy category.

After estimating the geospatial CO_2 removal capacity of DAC and finding the total capacity in, and out of, disadvantaged communities, we compare our removal estimates to the capacities suggested to be required to meet climate goals. Specifically, we compare to three capacity estimates:

- 720 $MtCO_2$/yr, which is the maximum 2050 DAC capacity estimated by the Princeton Net Zero America (PNZA) study (Larson et al. 2020).
- 464 $MtCO_2$/yr, which is the maximum 2050 DAC capacity in the USA across all scenarios modeled for the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (Byers et al. 2022).
- 134 $MtCO_2$/yr, which is the maximum 2050 DAC capacity estimated by the Low-Carbon Resources Initiative (LCRI) study (EPRI and GTI Energy 2022).

3. RESULTS AND DISCUSSION

3.1 Thermal Energy Potential of Sedimentary Basin Geothermal Heat for Direct Air Capture

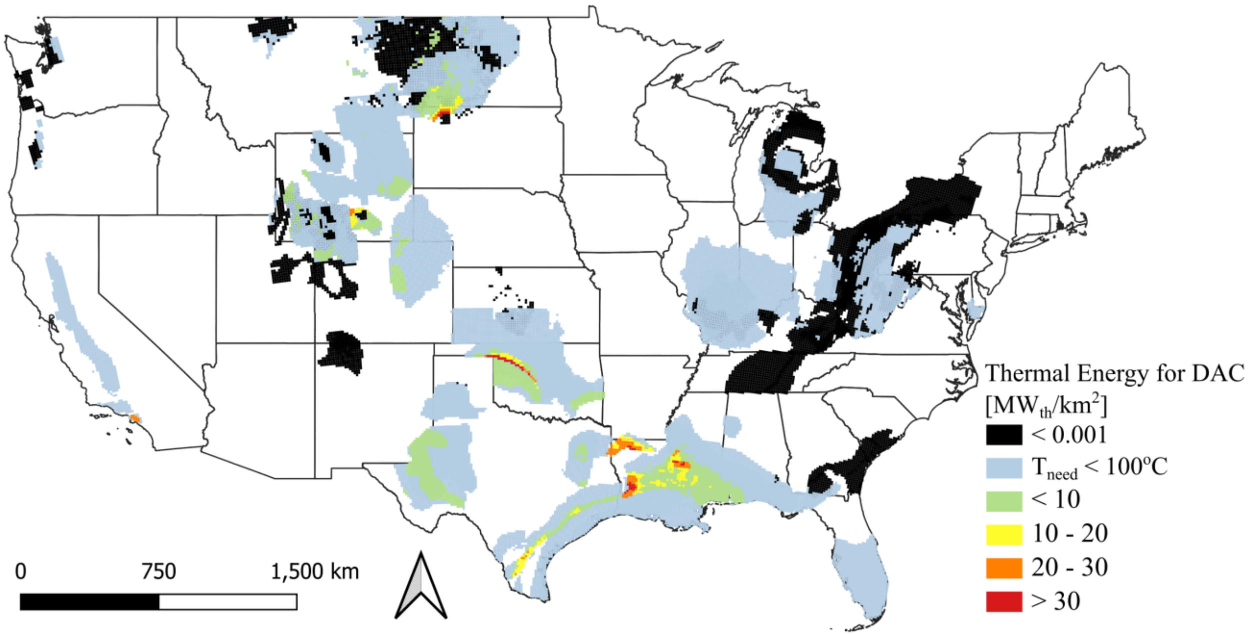

Figure 2: Geospatial Distribution of Sedimentary Basin Geothermal Heat that Could Provide Thermal Energy to Solid-sorbent DAC.

Figure 2 shows the quantity of sedimentary basin thermal energy available for DAC across the contiguous United States. As seen, most of the sedimentary basin resource base cannot provide thermal energy for DAC (colored in blue and black). Locations colored in black have insufficient reservoir transmissivity to support geofluid production flowrates amenable for direct use applications and locations colored in blue can provide thermal energy, but not at hot enough temperatures for DAC. Although not suitable for DAC, these regions could hold promise for future CO_2 sequestration (Ogland-Hand et al. 2023), provided CO_2 transportation infrastructure is developed.

Despite these locations with no/low heat potential for DAC, there are a variety of locations in the United States that could support solid-sorbent DAC. As seen in Figure 2, these locations include Louisiana, Mississippi, Oklahoma, Texas, Wyoming, California, and South Dakota. Considering that geothermal development in the United States is traditionally focused on the West, Figure 2 suggests that developing sedimentary basin geothermal resources for the purpose of providing heat for DAC could expand geothermal development to other areas of the country. The emergence of these locations in Figure 2 is attributed to their combination of high reservoir transmissivity and temperature.

Finally, numerous locations are void of sedimentary basin resources (colored in white). As previously highlighted in our study that introduced the nationwide database of sedimentary basin properties (Ogland-Hand et al. 2023), many areas of the country, such as Nevada and Arizona, lack sufficient data to fully characterize the subsurface or require additional effort to characterize the sedimentary basin resources. In other words, the data presented in this study likely underestimates the potential of sedimentary basins for DAC applications, and future work may increase coverage (and consequently DAC removal capacity) by extending the database to currently uncovered locations.

3.2 Geospatial Thermal Energy Demand of Solid-Sorbent DAC as a Function of Weather

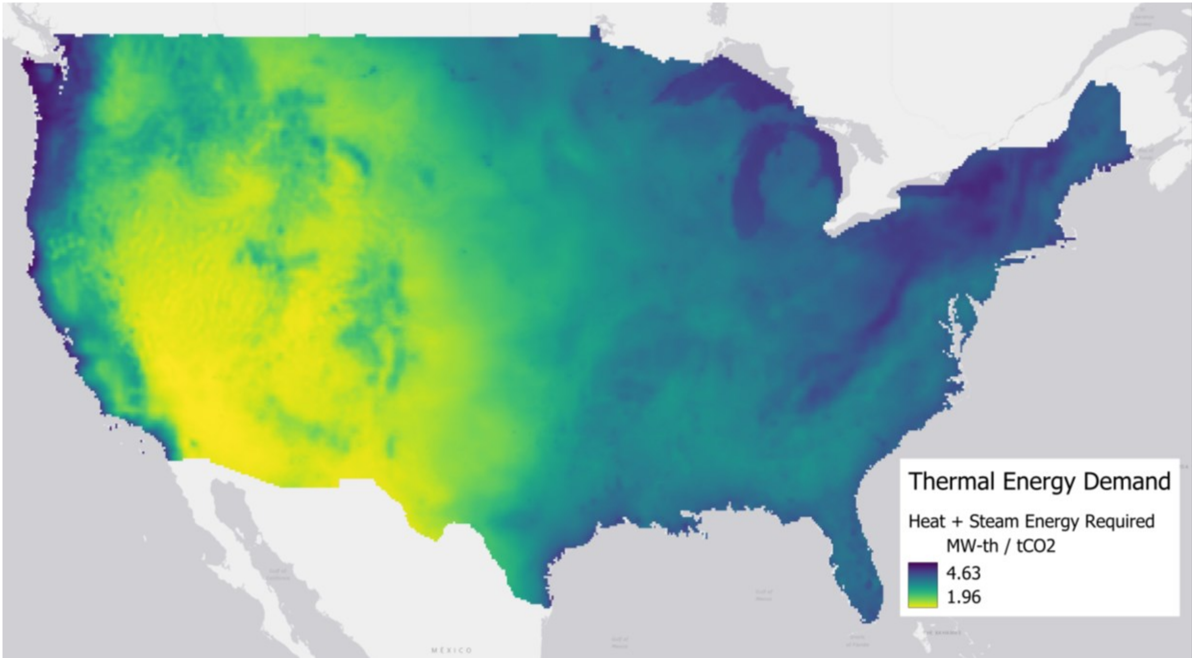

Figure 3: Geospatial Thermal Energy Requirements of Solid-sorbent DAC Averaged Across the 20 Years of Weather Data.

Figure 3 shows the thermal energy requirements of solid-sorbent DAC, which is driven by differences in air temperature and relative humidity. The thermal energy demand of the solid-sorbent DAC system modeled by Sendi et al. (2022) generally increases with increasing air temperature and relative humidity. Figure 3 shows that when this generalized DAC model is applied to an empirically based dataset of historical weather, this can result in over a factor of two difference in thermal energy demand across the United States. For example, on average, a DAC facility located in New York may require ~4.5 MWth/tCO_2 removed, while the same facility located in Arizona would only require ~2 MWth/tCO_2 removed.

As illustrated by the regional cohesiveness in the Mountain West in Figure 3, relative humidity has a larger impact on thermal energy demand of DAC compared to air temperature. For example, the regional thermal energy demand is not only lowest, but relatively consistent across the Mountain West where the relative humidity is low, even in the north despite a steep latitudinally driven air temperature gradient.

3.3 Geospatial Potential for Solid-Sorbent DAC Heated by Sedimentary Basin Geothermal Heat

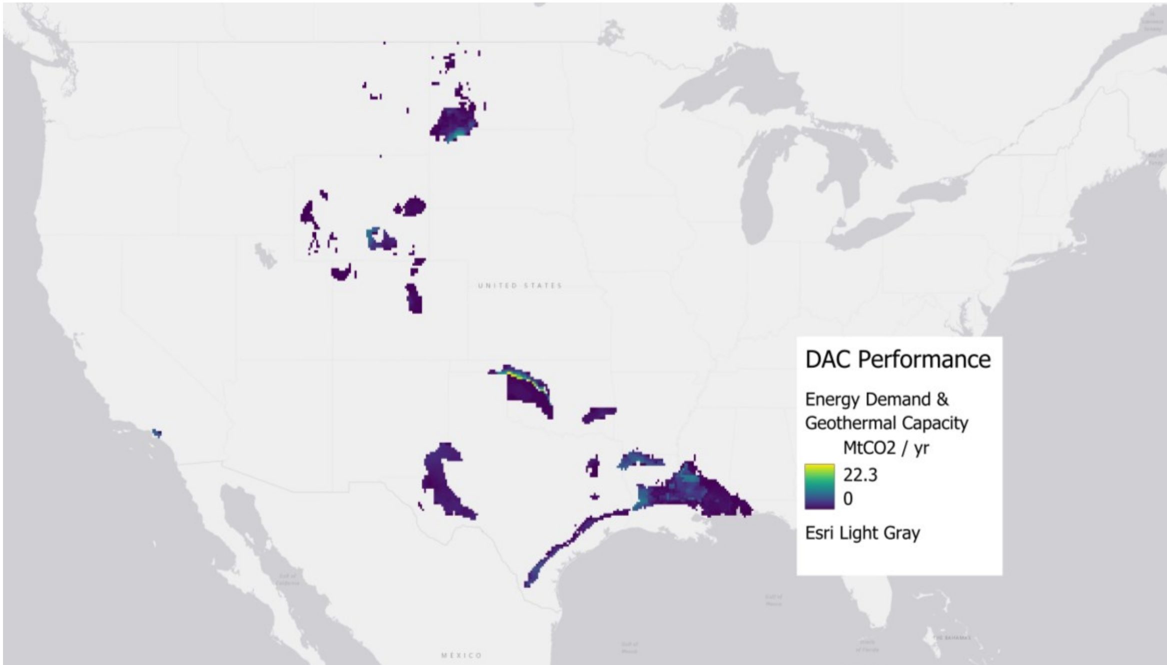

Figure 4: Geospatial Variations in Annual CO_2 Removal Capacity of Solid-sorbent DAC.

Figure 4 shows the CO_2 removal potential of solid-sorbent DAC when thermal energy demand (Figure 3) is met with sedimentary basin geothermal heat (Figure 2). As expected, the locations with the greatest CO_2 removal potential are those in which there is high geothermal energy in addition to persistent weather that favors lower thermal energy demand. For example, even though Louisiana and Mississippi have locations with high geothermal energy availability, the performance in Oklahoma and South Dakota is comparatively better given their climate tends to be more arid and cooler. Locations with near zero CO_2 removal potential have low capacities because there is a comparatively low quantity of sedimentary basin heat (Figure 2).

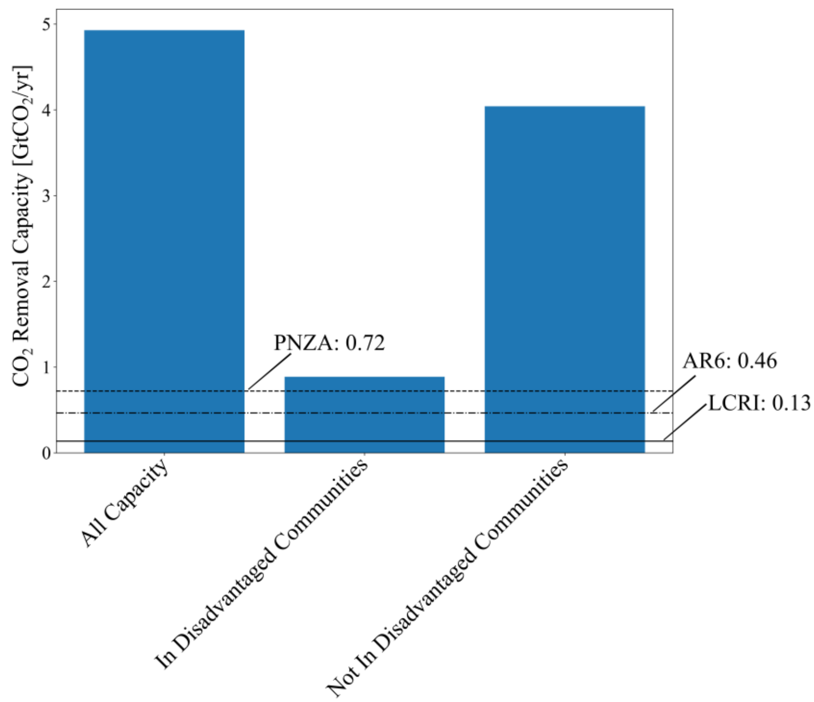

Figure 5: Total Potential Capacity of Solid-sorbent DAC When Sedimentary Basin Geothermal Energy is Used to Provide Heat and Portion of Capacity Located in Disadvantaged Communities. For reference, the maximum 2050 DAC capacity required in the USA is also included from a few different studies, as described in Section 2.3.

Figure 5 shows the total potential capacity of solid-sorbent DAC throughout the Contiguous US and demonstrates that sedimentary basin geothermal resources could support a total of 4.9 $GtCO_2$/yr of CO_2 removal potential. This potential capacity is an order of magnitude higher than the maximum DAC capacities suggested necessary to achieve energy transition goals, such as a net-zero economy in 2050. Further, there is also sufficient capacity for reaching energy transition goals, regardless of if this deployment occurs exclusively within, or exclusively outside of, disadvantaged communities. Overall, Figure 5 demonstrates that sedimentary basins may provide tremendous value to justice-centered pathways that meet mid-century energy transition via deploying solid-sorbent DAC.

4. CONCLUSIONS

In this study we estimate the potential that thermal energy from sedimentary basin geothermal resources may have for driving solid-sorbent DAC. We find that:

- There are sedimentary basin geothermal resources that can provide thermal energy for solid-sorbent DAC in multiple locations in the United States not typically considered for geothermal energy development (e.g., Louisiana, South Dakota). Further, there are many locations that have sedimentary basins with insufficient reservoir transmissivity or temperature for DAC, but that could provide CO_2 storage. As such, with sufficient CO_2 transportation infrastructure, it is possible to use the nation's sedimentary basin resource base to provide thermal energy for DAC and store CO_2.
- The locations with the highest potential for solid-sorbent DAC performance are not necessarily the same locations as those with highest potential for sedimentary basin heat generation. The thermal energy demand of the solid-sorbent DAC system considered in this study generally decreases with decreasing air temperature and relative humidity, whereas geothermal heat is independent of weather. As such, the locations with the highest DAC potential are those with both geothermal energy resources and with lower relative humidity and air temperature.
- Sedimentary basin geothermal resources could provide an order of magnitude greater DAC capacity than is needed to reach United States energy transition goals. In total, almost 5 $GtCO_2$/yr of removal capacity may be possible with sedimentary basin geothermal resources. Further, there may also be sufficient geothermal energy potential for reaching energy transition goals by prioritizing deployment in disadvantaged communities, or by refraining from development in those areas altogether.

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