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Communities conditionally support deployment of direct air capture for carbon dioxide removal in the United States

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Celina Scott-Buechler[1] ✉, Bruce Cain[1,2], Khalid Osman[1,3], Nicole M. Ardoin[1,4,5,6], Catherine Fraser[7,8], Grace Adcox[8], Emily Polk[9] & Robert B. Jackson[1,5,6]

Direct air capture has gained traction as a method for carbon dioxide removal. How and whether direct air capture can be deployed requires securing social license to operate, and increasingly demands environmental justice and just transition principles. Here we use a nationally representative survey to evaluate public perceptions of direct air capture, paired with focus groups to assess community perceptions across four communities in the United States: Houston, Texas; Monaca, Pennsylvania; Bakersfield, California; and Rock Springs, Wyoming. We find conditional support for direct air capture deployment among focus group participants, and majority support for direct air capture deployment among national survey respondents. The most important determinants of project support were procedural justice elements—in particular community involvement in planning and implementation—and anticipated community benefits in the forms of local infrastructure and workforce development, supporting the need to center environmental justice and just transition principles into project planning and implementation. Where concerns over environmental and health implications are strong, direct air capture may not gain local social license to operate, especially in communities with previous negative experiences with industry.

The Intergovernmental Panel on Climate Change (IPCC) has concluded that carbon dioxide removal (CDR) is needed to complement rapid decarbonization and phase-out of fossil fuels to meet ambitious global climate goals[1]. Compared with most other CDR methods, direct air capture (DAC) has smaller land and water footprints, and estimates of its global capacity range from 0.5 to 5 $GtCO_2$/yr by 2050[2,3]. Despite DAC's promise, only a handful of projects are operational[4]; scaling DAC to even the most conservative estimates of its potential will require technological improvements to decrease energy intensiveness and costs, which have been the focus of much of the DAC literature[5–7]. However, social considerations will also determine DAC's viability but have received far less attention from the scientific community[8,9].

Social science literature emphasizes the need to secure social license to operate (SLO) for large-scale infrastructural development, and to ground climate action in principles of environmental justice (EJ) and a just transition (JT)[10–15]. SLO is defined as "broad, ongoing approval and acceptance of society to conduct [an industry's] activities"[16]. While SLO originated in the mining industry with a primary focus on legitimizing corporate activities[17], recent scholarship has critiqued instrumentalist approaches to SLO[15,18]. Instead, this scholarship points to the need for critical evaluations of structural and ideological determinants, and dynamics of trust and equity between communities and developers[14]. Parsons & Luke (2021)[19] identify the frequent misuse of the SLO concept to "prove" support or opposition. Instead, SLO research must carefully examine nuanced public and

[1]Emmett Interdisciplinary Program in Environment & Resources (E-IPER), Stanford University, Stanford, USA. [2]Political Science, Stanford University, Stanford, USA. [3]Civil and Environmental Engineering, Stanford University, Stanford, USA. [4]Environmental Behavioral Sciences, Stanford University, Stanford, USA. [5]Woods Institute for the Environment, Stanford University, Stanford, USA. [6]Precourt Institute for Energy, Stanford University, Stanford, USA. [7]McCourt School of Public Policy, Georgetown University, Washington, D.C, USA. [8]Data for Progress, Washington, D.C, USA. [9]Writing and Rhetoric Studies, Stanford University, Stanford, USA. ✉e-mail: celinasb@stanford.edu

community perspectives on technologies themselves and the sociotechnical systems within which they will exist. Further, Batel et al. [20] identify "acceptance "as a passive relationship the community has with infrastructure, whereas "support" implies a more active and positive relationship, which may be beneficial to both projects and communities.

While SLO can encompass themes of equity and justice, EJ and JT take expressly justice-oriented approaches to industrial activities. EJ seeks to address the unequal distribution of environmental benefits and harms[11,21] while acknowledging the history of disproportionate harms low-income communities and communities of color have borne. A just transition seeks to build energy and climate solutions that center equity and justice for communities, especially those that have traditionally relied economically on carbon-intensive sectors or have suffered disproportionate health and environmental impacts of industrial activity[22–24]. Given recent pushback from community organizations to technologies with shared features, especially carbon capture and storage (CCS), and frequent conflation with these technologies, adopting JT and EJ frameworks may help assuage fears of DAC as a "false" climate solution that reinforces current injustices in infrastructure placement and pollution in poorer communities[25]. SLO, EJ, and JT are important lenses for infrastructure deployment, especially for stakeholders who are expected to interact most closely with the technology through geographic proximity, employment and other economic dependence, cumulative environmental burdens, or sociocultural ties to landscapes[26–29].

In 2021, the U.S. Congress allocated $3.5 billion for direct air capture and storage, representing the largest single government investment in the technology to date. This funding will support four regional direct air capture hubs that demonstrate "the capture, processing, delivery, and sequestration or end-use of captured carbon" and "could be developed into regional or inter-regional carbon network[s] to facilitate sequestration or carbon utilization"[30]. Perhaps recognizing the importance of securing SLO, especially through EJ and JT principles, the U.S. Department of Energy (DOE) requires applicants to submit community benefits plans detailing how projects will engage communities and offer financial, labor, and/or other benefits. Despite substantial policy movement on DAC, little is known about public perceptions of or equity considerations for DAC in the United States, or how communities that are proximate to potential DAC projects may respond.

Indeed, in the case of DAC—which, unlike some other climate infrastructure, does not provide immediate co-benefits that can be realized by the host community—it may be especially important to offer ancillary benefits like employment and community investment to enable acceptance of and, ideally, support for DAC[31]. Understanding whether, and under what conditions, communities might support DAC development locally will be critical to understanding whether DAC can be realized at scale. Indeed, schisms often exist between how the public conceives of infrastructural projects like renewable energy in the abstract and how local publics conceive of projects to be built near them[32,33], so acceptance must be examined on a project-by-project basis.

In this study, we bridge gaps in the CDR literature by presenting: (1) place-based perceptions of DAC and the specific socio-technical conditions under which it may be developed, (2) the shape communities may want community engagement and benefits-sharing to take, and (3) a comparative assessment of national public and community support for DAC to provide insights across broader socio-political acceptance (among the general public) and local community acceptance (among those who interact most closely with its infrastructure) of DAC. To do so, we use a mixed-methods approach assessing perceptions of DAC under various technology, policy, and implementation configurations. We conducted qualitative focus groups to explore which components of DAC might influence local perceptions of potential projects, including perceptions of risk, benefits, trade-offs, and equity. We then tested public salience of and support for DAC using a nationally representative survey, which included a conjoint analysis experiment to assess the relative importance of socio-technical dimensions that emerged in focus group discussions: funding mechanism, facility ownership, energy and heat source, level of community engagement, CO_2 transportation and storage, community benefits, and job creation. Combining findings from these approaches, we identify how implementation of existing policies and creation of future policies can effectively meet public and community needs through EJ and JT lenses, and potentially enable DAC SLO.

Results

Focus groups

Focus groups were conducted at four geographically and politically diverse sites proximate to CO_2 geologic storage opportunities and with recent carbon-intensive industry: Houston, Texas; Monaca, Pennsylvania; Bakersfield, California; and Rock Springs, Wyoming. Conversations ranged widely but fell into three categories: (1) environmental concerns and opportunities, (2) economic concerns and opportunities, and (3) stakeholder trust and community engagement. Woven into these categories were health concerns, which were often intertwined with other concerns (environmental or economic).

While only 61% of participants reported having heard of DAC prior to the focus group, 94.4% reported having "a little" knowledge or greater, and 81.9% reported "some" knowledge or greater at the end. When asked to reflect on their perceptions of DAC overall following a presentation and focus group discussions (post-survey), participants indicated a high likelihood of approving of projects in their communities, should the projects meet certain criteria (Fig. 1).

Environmental concerns. Discussion of environmental risks focused primarily on CO_2 transport and storage components, and less so on capture and energy production stages. This is corroborated by Arning et al.'s[34] findings that CO_2 transport and storage raised the most concern with respect to carbon capture and storage. The possibility of CO_2 leaking, and the potential health impacts of a leak, was a common source of worry. One Bakersfield participant raised the example of a CO_2 pipeline rupture in Satartia, Mississippi, which forced 200 residents to evacuate and some to seek medical attention. Pipeline-related concerns were also prominent in the Pennsylvania focus groups, where the community's recent experience with the fracking boom led to mistrust of pipelines and other infrastructure evocative of natural gas production and transportation.

Where storage was concerned, many participants returned to mineralization as the "safest" option, with similar reasoning used to support CO_2 utilization for long-lived materials. As one participant said, "carbon dioxide is injected into the ground, where it chemically reacts to become rock… okay, that sounds like it's the safest way to go." Another noted: "[I]f it's in liquid or gas form underground, it will leak up into and overtake our water table. It's inevitable," showcasing risk perceptions of geologic storage options shared by many. Participants also indicated concern that spent oil and gas wells might fill up over time if developers relied on them for storage.

Finally, participants concerned about climate change and local air pollution raised questions about the moral hazard of CDR. The possibility that DAC might allow companies to continue pollutive practices while greenwashing their public image was raised across all focus groups. In the words of one participant, "[companies are] not going to really reduce the overall carbon emissions. It's just going to be redistributed to other companies [who] have enough money to pay for the credit." One Wyoming focus group participant emphasized the energy-intensity of a practice with benefits that were difficult to grasp: "We are using high energy intensity to take elusive CO_2 out of the atmosphere to feed a business model that seems to be just like…it's smoke and mirrors. It's not something tangible that we need." Others worried that DAC might be a front for fossil fuels to sustain themselves without contributing real environmental and climate benefits. This was of particular concern in the scenarios where the DAC facility was powered by fossil fuels: "[I]t makes no sense to have this thing run by fossil fuels when it's supposed to clean the air and then companies are gonna go pay them for this carbon offsets scheme that's been going," one participant said.

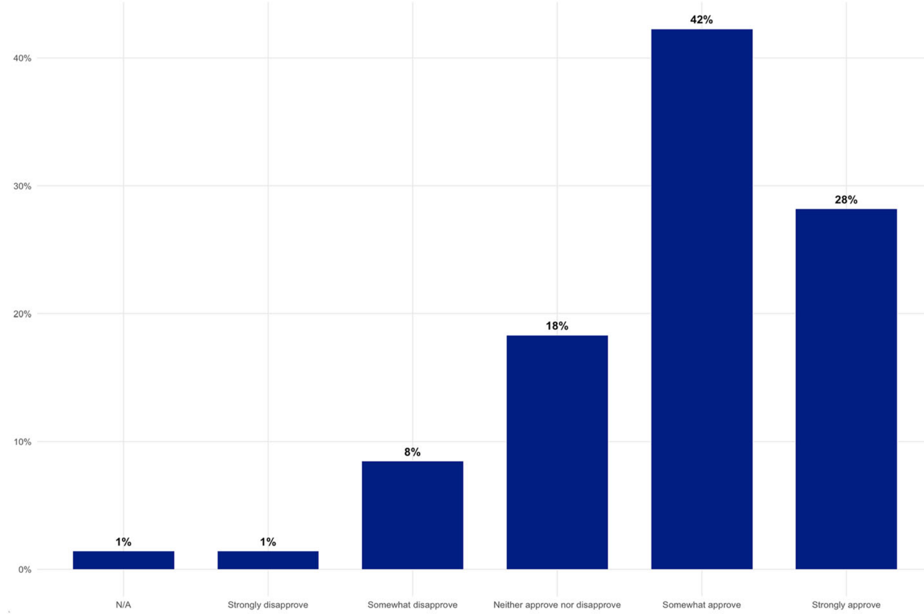

Fig. 1 | Post-focus group support for local direct air capture. Focus group participant responses to the question in the post-discussion survey, "[W]ould you overall approve or disapprove of a direct air capture project being built in or near your community?".

Environmental opportunities. Although environmental concerns were primarily local, the environmental opportunities participants identified were largely global. Many participants identified climate change as a growing threat and reasoned that DAC was likely an important part of the solution set. Some spoke favorably of DAC's capacity to "undo" climate-warming pollution. California participants cited the state's increasingly devastating wildfire seasons and expressed beliefs that not enough was being done to curb climate effects like these. A few participants expressed hope that a DAC facility in their community could be their contribution to addressing the climate crisis. As one California participant said: "I feel this is something that is long overdue. We really need to think about the air or we won't have an Earth inhabited by us." In the Pennsylvania focus group, where views on anthropogenic climate change were more split, a few participants urged that DAC be presented with more of a climate frame while others pushed back on climate change being a relevant issue for the area. In Wyoming, climate change was highly contentious—both whether the climate was changing and whether it was caused by humans—with a few participants urging that a climate change frame not be used to discuss DAC, and counseled instead for an economic diversification frame.

At the local scale, participants mistakenly assumed that if DAC were "cleaning up" carbon dioxide, it might be able to address other forms of air pollution. When corrected, many asked whether the technology might be adapted to tackle co-pollutants, arguing this would make the technology more acceptable or even desirable to their community: "[A]nother thing that I think would…help alleviate a lot of fears, especially when it comes to… increased particulate pollution from dust and whatnot, if there would be a way to, I don't know, like, incorporate, not just a CO_2 filter. But if we can incorporate something like, you know, other types of filters as well".

Economic concerns. Many participants expressed confusion over the economic model for and feasibility of DAC. They also worried that their communities would be left with the financial responsibility for future build-out and/or maintenance of local facilities, which they had seen with other infrastructure projects. Others raised the concern that corporations would reap the economic benefits at the expense of the community. Participants recognized the ability of a DAC facility to create jobs, but questioned whether the quality or quantity of jobs promised would be delivered. Jobs presented by a DAC hub would have to be of the same, if not higher, quality compared with existing industries like oil and gas to attract an experienced workforce. Indeed, several participants were skeptical that companies would deliver quality jobs, as measured by wages and opportunities for worker bargaining power (whether as part of a union or in direct negotiations). Labor benefits were the most cited opportunities that a DAC Hub might present communities.

Participants also worried DAC would strain local infrastructure. In California, there was recognition that waste processing facilities were disproportionately located in low-income communities and communities of color, which might mean that the burden of waste and/or other pollution from DAC would fall on the same communities. Finally, recognition of DAC's intensive energy requirements led some to worry that powering DAC using existing energy resources might raise energy costs for ratepayers. At the very least, participants reasoned, a DAC hub should not worsen the community's economic wellbeing, especially through something as important as energy costs.

Economic opportunities. Across focus groups, participants raised the possibility of community-owned or co-owned DAC facilities. While many had trouble imagining what such an economic model might look like, the opportunities for community benefit and influence over decision-making were sources of excitement. Particularly in California, participants suggested that a community-owned DAC facility could provide real benefits to a community in which oil and gas companies otherwise dominate local politics. In addition to offering workers greater choice for jobs outside of fossil fuels, lessening municipalities' economic reliance on these industries could restimulate public political power in a region otherwise prone to industry capture. The need to decrease how much power fossil fuel companies and other pollutive industries wielded in local politics was also raised in Texas and Pennsylvania, linking political stability with economic choice. Finally, while some viewed DAC development as a threat to residential energy costs, others saw it as an opportunity to expand energy infrastructure and sustainability. One California participant noted: "And if we allocate space for a solar farm that is used...to fuel this place, any excess would benefit us directly…we can reduce our electric bill."

Stakeholder trust and community engagement. Stakeholder trust was a common theme when discussing governance of DAC. Participants asked: who should oversee project construction and operation? And especially, who should be able to make decisions about hazard prevention and risk monitoring? Views on these questions diverged. Trust in local government was generally low across sites, with several references to local corruption; however, there was also a desire for public participation in and oversight of a potential DAC facility. Across focus group sites, participants questioned how developers would be held accountable for project safety and efficacy, and many doubted that sufficient enforcement mechanisms would be put in place.

Many participants proposed direct community oversight. This would make projects fairer, they reasoned—giving community members a seat at the table for planning and implementation of a project that would affect them—as well as safer, placing a check on private interests. In addition to physical safety measures like monitoring systems for leaks, seismic activity, and other environmental risks, many participants urged safeguards against social and labor risks. Many saw unions as an entity that could support this need, though others were either ambivalent toward or even mistrustful of unions, worrying about economic barriers to union participation.

While community oversight was important for participants who supported prospective local DAC projects, the private sector was seen as a necessary partner for the construction stage. As one participant in Pennsylvania noted, "I don't think you can gather a group of [a] community's people and expect them to know what to do for direct air capture… nobody's gonna be knowledgeable enough to lead this, to build it. You got to have somebody from a company that knows what they're talking about." Most participants expressed preferences for working with companies that could demonstrate experience, but there was disagreement on what kinds of companies would best satisfy that requirement. Many thought that dedicated DAC companies would be the obvious choice, reasoning that if they only worked on DAC, they likely had greater experience with the technology. The possibility of fossil fuel companies playing a role was also discussed; several participants identified oil and gas as having experience with subsurface activities. Perceptions on whether fossil fuel companies could be trusted even for non-extractive practices were divided, however, with other participants emphasizing fossil fuel companies' track records of pollution, injustice, corruption, and lack of transparency. In large part, perceptions of the fossil fuel industry and whether it should be allowed to participate in DAC deployment were linked to participants' past experiences with extractive industries, especially the fossil fuel industry. This conclusion supports the findings of Gough et al. [35]., which showed that levels of trust in prospective CCS developers were linked to previous personal and community experiences with industries like shale gas.

National survey

2197 participants were recruited for the survey. Those excluded from the study results included respondents who did not complete the survey, failed the simple attention check, or were in the fastest 5% of respondents (suggesting low engagement), leaving a final sample size of 1633. Using standard rake weighting, responses were weighted for national demographic representativeness per the American Community Survey across sex, race, ethnicity, education, age, and region[36].

A conjoint experiment assessed preferences for components of a potential DAC project (see *Methods* for details). Average marginal component effects (AMCEs) were calculated for socio-technical features tested: funding source, facility ownership, energy and heat source, level of community involvement, CO_2 transportation and storage, level of community benefits, and job creation (Fig. 2). We find that DAC funded through a tax on members of the public ("Economy-wide tax" or "Income tax on the wealthiest Americans") was significantly less popular compared with DAC financed using private sector funds, whether voluntary or through targeted taxation ("Tax on polluting industries", "Closing tax loopholes for polluting industries", or "Private funds") (−0.016 [−0.029 – −0.003], $p = 0.014$). We also find significantly higher support for DAC with high levels of community involvement than with low levels of involvement (0.016 [0.004–0.028], $p = 0.009$), and that plans guaranteeing long-term jobs are significantly preferred to those offering short-term or no jobs (0.022 [0.009–0.035], $p < 0.001$). Most features do not have statistically significant results, and those that do have effect sizes of <5%, most likely reflecting a lack of fully formed opinions on the issue, given low prior awareness of DAC. Both focus group discussion and conjoint results highlight the importance of minimizing public costs while maximizing community involvement and job creation. Each line of evidence allows us to validate the other, and also suggests that the conjoint effect sizes (AMCEs) may increase with more substantive engagement with the topic.

Our survey shows that only a small share of Americans have interacted with the topic of DAC. Indeed, 72.44% of respondents reported having heard "nothing at all" about DAC before participating in the survey. Among those who had, a majority self-reported to "somewhat support" or "strongly support" DAC being built in their community (66.67%), near their community (65.33%), or in the United States (71.56%) (Fig. 3). Higher levels of support than opposition align with Satterfield et al.'s[37] findings, who surveyed U.S. and Canadian publics located near a proposed DAC project in the Pacific Northwest and found 58% support and 13% opposition among survey-takers.

Given low prior knowledge of DAC, most survey respondents learned about the technology through our survey. After providing descriptions of DAC and its project components (Table 1) along with images of what DAC might look like in communities[38], we asked respondents to provide their impressions of DAC. Among those who had heard of DAC before the survey ($N = 450$), 60% said they would "somewhat support" or "strongly support" DAC in the U.S. before receiving more information and 71% after reading more, whereas 56% indicated they would lend support for DAC in their communities prior to receiving more information and 67% indicated support afterward (Fig. 4).

Republicans and Independents were significantly less likely than Democrats to support the development of DAC in and near their communities and in the U.S. (Table 2). Men were statistically likelier than women to support DAC in or near their communities, and higher income bracket respondents were significantly less likely to support siting DAC near or in their communities (Table 2). While a majority of respondents indicated that they would support DAC in their community, there was greater overall support for DAC when cited nebulously "in the U.S." (Fig. 4), which aligns with research conducted on carbon capture and storage and suggests that "not-in-my-backyard" sentiments may be at work[39], even if the margins are relatively small.

In addition to demographic indicators of support for DAC, the model tested the effects of (1) perceived need for local jobs and trust that new industries will deliver jobs of the quality and quantity promised, (2) strength of community ties as a proxy for trust in capacity to negotiate project terms that would benefit the community, and (3) belief in anthropogenic climate change and its interaction with partisan affiliation.

We find statistically significant positive relationships between perceived need for jobs in one's community and support for DAC locally and nearby. We also find a correlation between trust that new industries that promise jobs will deliver them in quality and quantity and support for local or nearby DAC. This suggests interest in DAC as a prospective job creator. However, where communities do not trust that industries will create the jobs they promise, perhaps informed by prior negative experiences with new industries, they are likely to show lower levels of support.

Model results also indicate positive correlations between ability to rely on one's community and support for DAC locally and nearby, and no significant association with support for DAC in the U.S. This corroborates sentiments expressed in the focus groups; participants expressed varying levels of trust that their community would successfully negotiate a beneficial project with a developer, given weak intra-community ties and/or trust (Table 2).

Finally, we find that belief in anthropogenic climate change is only a statistically significant predictor of support for DAC in nearby communities or generally in the U.S. (Table 2). This corroborates Wyoming focus group findings, in which other considerations (like job creation and community participation) were more important to participants than the potential for addressing climate change. Examining interaction effects between partisan identity and belief in anthropogenic climate change, Republicans who believed in climate change supported DAC in and near their communities

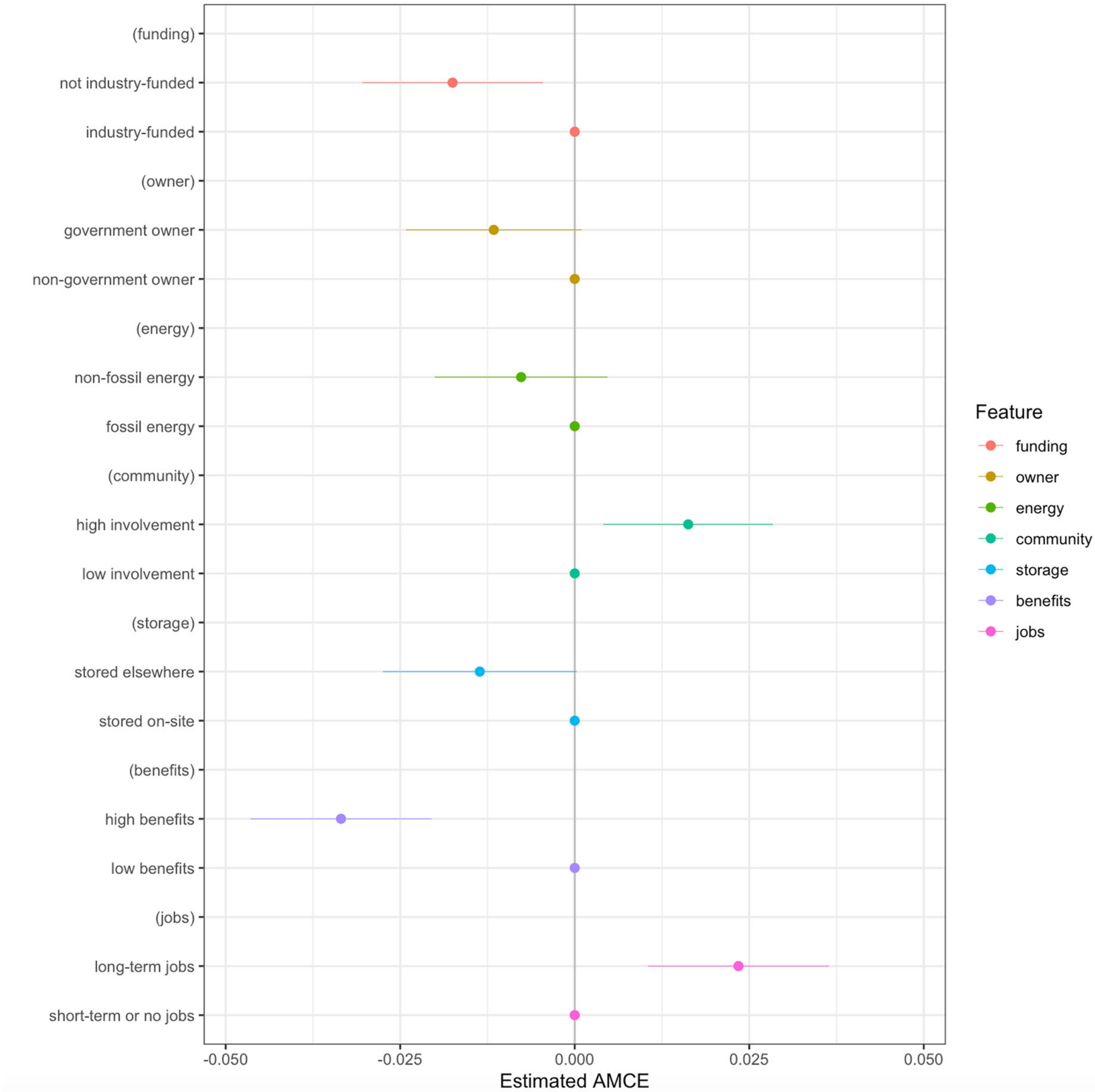

Fig. 2 | Policy preferences for local direct air capture siting. Average marginal component effects (AMCEs; means plus 95% confidence intervals) for DAC socio-technical attributes.

and in the U.S. at higher rates, as did Independents who believed in climate change for local siting of DAC (Table 2).

To test whether environmental injustice burden (CDC EJI) or living in a community with recent or ongoing coal plant closures affected support for DAC, we added these variables to the model. Our results were not statistically significant, suggesting that environmental justice and transitioning communities will have diverse responses to DAC that are based more on the variables described above (Supplementary Fig. 1). This is supported by the findings of our focus groups, all of which are designated energy communities and three—Bakersfield, CA, Houston, TX, and Monaca, PA—in the 75th percentile of the CDC's environmental [in]justice index (EJI).

Discussion

This study provides mixed-methods analysis of perceptions of prospective DAC deployment. Although broad public support will be useful for advancing policies that enable DAC deployment and scaling, community acceptance and buy-in are instrumental in achieving SLO for specific projects.

We found conditional acceptance of DAC—both in focus groups and in the national survey—which aligns with research on renewable energy showing that communities lend conditional acceptance for projects depending on levels of democratic participation, community benefit, transparency, and stakeholder trust[40–43]. A majority of focus group participants believed that, under the right conditions, their communities could support local DAC deployment. Participants expressed preferences for substantive community engagement and investment, especially through job creation, ideally beginning in the early project stages. Most focus group participants expressed greater interest in projects that had some degree of community ownership and oversight, with all groups concluding that cooperative decision-making would more likely yield successful outcomes than unilateral decision-making by developers. National survey results point in a similar direction: the national conjoint experiment shows that even among members of the public with less information on DAC (a feature of survey research), levels of community participation and job creation increased support for local DAC projects. Further, perceived ability to rely on one's community to solve challenges was significantly correlated with

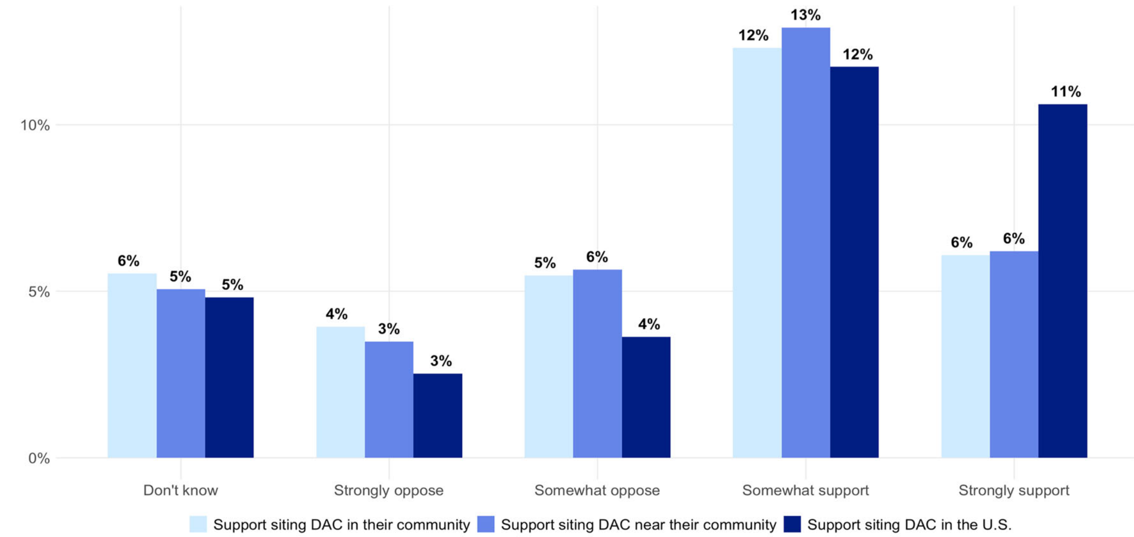

Fig. 3 | National survey support for direct air capture. Levels of support or opposition to DAC among all survey participants in their community (light blue), near their community (medium blue), and in the United States (dark blue).

Table 1 | Possible DAC project components for conjoint experiment

Funding Source	*Funded by industry*	Tax on polluting industries; Closing tax loopholes for polluting industries; Private funds
	Funded by members of the public	Economy-wide tax; Income tax of the wealthiest Americans
Developer & Owner	*Government owner*	National government; State or local government
	Non-government owner	Cooperatively owned by community members and community orgs.; Fossil fuel company; Direct air capture company
Energy Source	*Fossil energy*	New or expanded fossil fuel energy; Existing electricity grid energy
	Non-fossil energy	New or expanded nuclear energy; New or expanded wind/solar energy; New or expanded geothermal energy
Community Involvement in Project	*Low involvement*	No consultation; Written comments accepted
	High involvement	Workshops held to collect feedback; An elected community advisory board has voting power over project decisions; Community members have direct voting power over decisions
Carbon Dioxide Transportation & Storage	*On-site storage*	Used for enhanced oil recovery on-site (extracting oil while potentially storing some carbon dioxide); Stored underground on-site in depleted oil and gas wells (injecting into empty wells); Stored underground on-site using mineralization (injecting underground to turn carbon dioxide into rock)
	Off-site storage	Transported out of community by CO_2 pipeline to be stored elsewhere; Transported out of community by trucks or rail to be stored elsewhere
Project Costs Reinvested in Community	*Low benefits*	None; 1%
	High benefits	5%; 10%; 20%
Jobs creation	*Short-term or no jobs*	No local jobs guaranteed; Short-term local jobs guaranteed for construction without unionization; Short-term local jobs guaranteed for construction with unionization
	Long-term jobs	Long-term local jobs guaranteed without unionization; Long-term local jobs guaranteed with unionization

support for local DAC development. These findings align with Bergquist et al. [44]., who show that linking climate policies to economic and social issues increases public support for those policies. Our results indicate that providing communities with tangible economic and social benefits increases socio-political (large-scale) as well as community (local scale) support. Future research is necessary to elucidate models for community ownership of large-scale CDR like DAC, given participant interest and recent calls for centering communities in DAC development (e.g. Batres et al., 2020). Further, government policies that require the private sector to pay for CDR (e.g. a carbon take-back obligation per Jenkins et al. [45]) while empowering communities and workers to control the means of CDR production should be explored.

Questions remained about whether and how the conditions for DAC development might materialize, with attention to equity across planning, construction, and operation phases. Skepticism over equity usually cited personal or community experiences with pollutive industries—especially the fossil fuel industry, which has a well-documented history of environmental injustice[46,47]. Potential hazards often dominated discussion, aligning with psychological research pointing to heightened risk perceptions of hazards seen as unknown, unfairly distributed, or with the potential for sudden and catastrophic consequences[48,49]. Given heightened risk perceptions of new technologies, benefits delivered to host communities may need to be more substantial to garner support, as compared with projects seen as less risky. This is especially so in communities with negative experiences with industry, which inform perceptions of new projects[50]. Indeed, for infrastructure that shares characteristics or first movers with the fossil fuel industry, such as CCS or DAC, trust in equitable and transparent outcomes may largely rely on communities' past experience with the fossil fuel industry[35]. Indeed, in some cases, negative experiences led participants to draw a line: if led by a fossil fuel company, a DAC project was not to be

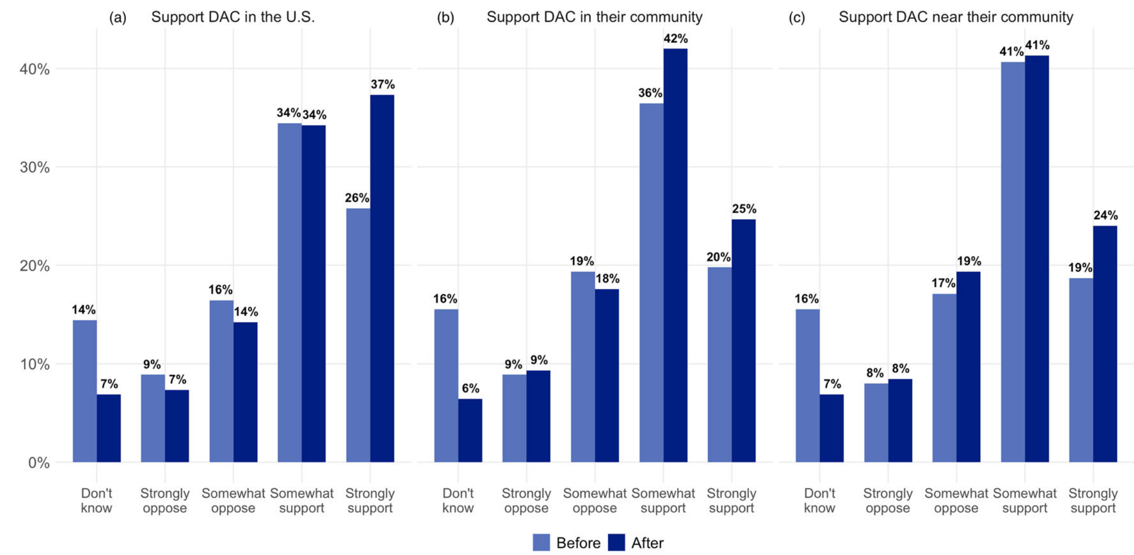

Fig. 4 | National survey support for direct air capture before and after provision of additional information. Levels of support or opposition toward DAC in (**a**) their community, (**b**) near their community, (**c**) in the United States pre- and post-survey among respondents who indicated having heard "only a little," "some," or "a lot" about DAC before taking the survey. Light blue indicates perception before taking the survey, while dark blue indicates perceptions at the end of the survey.

Table 2 | Determinants of support for direct air capture

	In your community	Near community	In the United States
Intercepts: Strongly opp. | Somewhat opp. Somewhat opp. | Somewhat supp. Somewhat supp. | Strongly supp.	−2.286 (0.315)*** −0.896 (0.306)** 1.299 (0.308)***	−2.086 (0.316)*** −0.712 (0.306)** 1.550 (0.310)***	−2.052 (0.3178)*** −0.828 (0.3067)** 1.028 (0.3066)***
Perceived need for jobs in one's community (numerical)	0.296 (0.086)***	0.274 (0.087)**	0.159 (0.086)*
Trust that industry will deliver promised jobs (numerical)	0.179 (0.073)**	0.171 (0.072)**	0.105 (0.072)
Reliance on one's community (numerical)	0.152 (0.041)***	0.094 (0.041)**	−0.053 (0.041)
Belief in anthropogenic climate change (numerical)	0.031 (0.095)	0.206 (0.098)**	0.256 (0.097)**
Party - Republican (categorical)	−0.987 (0.201)***	−0.659 (0.202)***	−0.496 (0.200)**
Republican x Belief in anthropogenic climate change	0.610 (0.119)***	0.357 (0.120)**	0.373 (0.120)**
Party - Independent (categorical)	−0.789 (0.208)***	−0.354 (0.211)*	−0.134 (0.210)
Independent x Belief in anthropogenic climate change	0.277 (0.128)**	0.158 (0.130)	0.069 (0.129)
Age (numerical)	−0.010 (0.003)**	−0.007 (0.003)*	0.001 (0.003)
Education (numerical)	0.097 (0.052)*	0.053 (0.052)	0.047 (0.053)
Middle- to high-income household (binary)	−0.234 (0.127)*	−0.254 (0.128)**	−0.068 (0.128)
Male (binary)	0.503 (0.113)***	0.522 (0.113)***	0.342 (0.113)**
Non-white (binary)	−0.330 (0.125)**	−0.196 (0.126)	−0.351 (0.125)**

Ordered logistic regression results for end-of-survey question, "Based on what you now know, to what extent would you support or oppose building direct air capture (DAC) facilities?" in Estimate (Std. Error) format. Significance of $p \leq 0.001$ indicated with '***', of $p = 0.05$ with '**', and of $p = 0.1$ with '*'. R^2 Nagelkerke: 0.599, 0.498, 0.482.

trusted. Regional variability in project preferences did occur, however: In Wyoming, for example, having a fossil fuel company lead the project was largely seen as an asset, especially with regard to employment.

A minority of national survey respondents had heard of DAC prior to taking the survey; even so, a majority indicated they would support DAC after learning about the technology. This is supported by Satterfield et al. [37]., who found high levels of support for DAC in the Pacific Northwest, despite reservations. It may be that self-reported levels of support ahead of projects differ from actual levels of support during and after projects' completion, but we are encouraged that our mixed-methods, national and local results indicated similar levels of support and project-level preferences. Given the importance of message framing to perceptions of CDR[8,51], future research is necessary to elucidate how information about DAC is being relayed to the public—its media, framing, and messengers—and the effects this has on perceptions of DAC.

The overall openness to accepting DAC infrastructure build-out provides nuance to a national discussion that assumes climate infrastructure will evoke not-in-my-backyard (NIMBY) sentiments. As discussed in Devine-Wright (2009)[52], research should focus on place attachment and identity, along with levels of awareness and involvement. While this alternative framework explains the qualitative analysis of our focus group discussions, our national survey showed that as household income brackets increased, favorability for DAC in one's community decreased. This suggests that wealth—and thus power—may play an important role in place-protective responses to climate infrastructure. Future research should investigate the role of social and political power in NIMBYism-alternative

Table 3 | Demographic profiles for each focus group site

Site	Demographics	Below Poverty Line
Houston, TX	23% Black, 7% Asian, 47% white, 1% AI/AN, 45% Hispanic	20%
Beaver County, PA	7% Black, 1% Asian, 90% white, 0% AI/AN, 2% Hispanic	11%
Bakersfield, CA	7% Black, 7% Asian, 58% white, 1% AI/AN, 52% Hispanic	16%
Sweetwater County, WY	1% Black, 1% Asian, 94% white, 2% AI/AN, 16% Hispanic	9%

frameworks. Further, while it is important that policies require developers to provide benefits to local communities, especially those with cumulative environmental burdens, it may also be important to investigate policy and legal structures for requiring wealthy communities to assume their fair share of climate infrastructure burdens—communities that in the national survey were least likely to support local DAC deployment. This is especially important in the case of DAC, which may seek to repurpose fossil fuel geographies and even infrastructure that is unevenly and inequitably distributed[53].

Our results have several applications. First, they demonstrate the importance of community economic benefits and ongoing community engagement to building support for DAC in host communities. We also show that, although secondary to social and economic considerations, technological aspects of DAC can be important to informing SLO. Given DAC's early stages of research, development, and deployment, an opportunity may exist to shape the technological features of the technology in ways that can improve its likelihood of achieving SLO in communities. As found in Cox et al. [9]., for example, some focus group participants mistakenly assumed DAC could remove other forms of air pollution, and others asked whether this was a possibility, indicating that tangible benefits like these might help build support for projects. This link between perceived benefits and support for climate engineering technologies is supported by research on other CDR methods and solar radiation management[54,55]. Many of our focus group participants also identified DAC's high energy demand and expressed concern about implications for energy security, reliability, and costs. Improvements in DAC efficiency and the ability to power DAC down in periods of exceptional grid demand (e.g., peak hours or during heatwaves) may help allay community concerns.

Our research elucidates some of the preconditions for acceptance of, and potentially even support for, DAC. SLO founded in EJ and JT principles is likely to be responsive to levels of community engagement and benefits, with particular attention to past industrial harms to host communities. While DAC may provide opportunities for a just transition in communities currently reliant on carbon-intensive industries like fossil fuels, work is needed to engage communities early and in an ongoing manner in project decision-making. Policies that encourage this kind of community self-determination, including ownership of projects, may be important to DAC's success. Policies that provide public financing for projects such as the U.S. Infrastructure Investment and Jobs Act should especially prioritize pathways for community engagement, leadership, and ownership with particular attention to EJ and JT needs in low-income, fence-line, and communities of color, while also considering how policies can encourage fair-share adoption of climate infrastructure in wealthy communities.

Methods

This study pairs a national survey with focus groups in Houston, Texas; Monaca, Pennsylvania (with Beaver county-wide participants); Bakersfield, California; and Rock Springs, Wyoming (with Sweetwater county-wide participants). Focus group research sought to understand place-based perceptions of prospective DAC projects. The national survey complemented this by measuring existing knowledge of DAC and levels of support for prospective projects within respondents' communities, nearby, or in the United States once respondents had been provided information about the technology. Both protocols were both granted approval by the Stanford University Institutional Review Board (IRB).

Focus groups

Deliberative focus groups have been used across a range of industrial projects to understand public perceptions in greater detail than other social science research methods like surveys typically provide[56–59]. With their smaller sample size, focus groups are not intended to be representative of the public at large; rather, they can uncover "complex personal experiences, beliefs, perceptions and attitudes of the participants through a moderated interaction"[60].

Communities were chosen for their proximity to long-term CO_2 geologic storage opportunities[61] and recent or ongoing carbon-intensive industrial projects—criteria laid out by Congress in IIJA. Areas with a heavy concentration of fossil fuel activities also presented opportunities to explore DAC in the context of a JT for industrial workers and fossil fuel-dependent local economies[62]. We sought geographically and demographically diverse communities across states with different political leanings in national politics (California strongly Democratic, Wyoming strongly Republican, Texas mostly Republican, and Pennsylvania a swing state), and across a diversity of city/town size (Houston a large metropolitan area, Bakersfield a mid-sized city, Monaca a small town near a large metropolitan area, and Rock Springs a relatively remote town). Focus group participants were recruited using regional market research recruitment firms with the objective of securing focus groups as representative of the community as possible across age, gender, income, and political affiliation. Across the four sites, we had a total of 73 participants. Demographic profiles of the communities we conducted focus groups are presented in Table 3; a demographic summary of focus group participants can be found in the Supplementary Information.

Pre-focus group surveys assessed self-reported prior knowledge of CDR, DAC, community benefit agreements (CBAs), and related concepts (see *Data Files, Replication/Methods/Focus Groups/1_Pre-Survey*). Participants were then given a presentation with information on CDR, DAC, CBAs, and related concepts (see *Data Files, Replication/Methods/Focus Groups/1_Presentation*).

We sought to assess public and community perceptions (perceptions of deployment in one's community) of DAC on its own, as well as the effects of participation in decision-making and benefits on acceptance of or opposition to projects. To this end, focus groups assessed knowledge and perceptions of one common tool for benefit sharing: community benefit agreements (CBAs). CBAs are legally binding contracts negotiated between project developers and a group of community representatives that lay out financial and other benefits a community will receive over the course of the project[63]. While CBAs are often used transactionally to "buy" community acceptance by developers rather than meaningfully co-produce projects with communities and equitably and transparently share benefits, they closely resemble the U.S. Department of Energy's required community benefits plans for the DAC Hubs program and can, under the right circumstances, be vehicles for genuine partnership between project developers and community members[64–66]. It was therefore presented to participants as an umbrella concept for multiple forms of community engagement and benefits-sharing.

We iterated on our presentation draft with experts to make it as informative, neutral, and balanced as possible, providing technical information alongside potential benefits and risks. To address potential conflation between DAC and/or CDR with CCS, we provided a short description of the concepts' similarities and differences; where participants conflated the technologies in discussion, facilitators gently corrected them.

Table 4 | National survey sample demographics

Sex	Female: 55.55%; Male: 44.45%
Race	American Indian or Alaska Native: 1.84%; Asian: 3.31% Black or African American: 11.45%; White: 73.91%; Hispanic or Latino/a: 7.04%; Other Race: 2.45%
Household Income Bracket	Low (<\$52,000): 58.30%; Middle (\$52,001–\$156,000): 35.82%; High (>\$156,001): 5.88%
Education (highest degree)	No high school diploma: 4.04%; High school diploma or equivalent: 28.78%; Some college, but no degree: 32.03%; Associate's degree: 7.47%; Bachelor's degree: 18.00%; Advanced degree (i.e. master's/PhD): 9.68%
Political Party	Democrat: 33.13%; Republican: 32.52%; Independent: 24.68%; Something else: 9.68%
Age Group	18–29: 19.17%; 30–44: 26.45%; 45–54: 17.45%; 55–64: 16.04%; 65+: 20.88%

Previous research indicates that presenting climate change-related topics in locally relevant terms can increase engagement[67,68]. More recently, research has shown that political polarization in the United States often leads self-identified Republicans to indicate lower levels of support for policies under a "climate change" frame as opposed to one of "extreme weather," whereas self-identified Democrats demonstrated higher favorability[69]. Therefore, while the presentation remained identical in most respects across sites, slides providing context on CDR were tailored to local political leanings: Bakersfield, CA, and Houston, TX, presentations included mention of climate change, whereas those for Beaver County, PA, and Rock Springs, WY, did not. Across focus groups, we described what DAC fundamentally does: remove CO_2 from the atmosphere for permanent storage. For sites where we tried to avoid mentioning climate change, we said as at other sites that there was "increased interest and money going toward DAC," but left out that this interest came out of a desire to address climate change. We note, however, that participants quickly identified where this interest was coming from, often linking it to "ESG" or "green" goals if not climate directly, and discussing the pros and cons of a new industry emerging out of societal goals they didn't agree with. Those who did believe in climate change at these sites cited it as a rationale for DAC (though secondary to social and economic reasons, as was found across sites—see *Results*).

In order to match participants' responses before and after the focus group, each participant was given an unmarked manilla folder to place their pre-focus group survey in and asked to keep track of it for the duration of the event; following discussions, they were given post-focus group surveys with a similar set of questions tracking knowledge of CDR, DAC, community engagement mechanisms, and related concepts (see *Data Files, Replication/Methods/Focus Groups/5_Post-Survey*), which they placed in the same manilla folder before leaving. This allowed us to assess changes in participant knowledge and perceptions before and after the focus group.

Facilitators from the research team guided focus group discussions (see *Data Files, Replication/Methods/Focus Groups/4_Facilitator Instructions and Prompts*), which were recorded. Groups were provided with a list of potential features of a DAC project (*Methods*, Table 1) and guided to consider the best-case scenario for a DAC project, then work backward to consider less-than-ideal scenarios and how those might impact their support of or opposition to a project. At the end of the discussion, a representative from each focus group presented takeaways to the larger group. This provided the research team with an additional check on their assessments of the focus group discussions and allowed for transparency between groups.

Focus groups recordings were transcribed maintaining participant anonymity and qualitatively coded[70] using NVivo. Some codes were determined deductively (a priori) based on the discussion questions: environmental concerns and opportunities, and economic concerns and opportunities. The third code group, stakeholder trust and community engagement, was analyzed using a combination of a priori and inductive (emergent) codes: community engagement, about which participants were asked directly, and stakeholder trust, which emerged while coding transcripts.

National survey

Data for Progress, a national polling firm, fielded the survey (see *Data Files, Replication/Methods/National Survey/1_Full Survey*). Sampling was conducted using probability-based methods through PureSpectrum Marketplace Platform, a national web panel provider, which uses online advertisements, text messages, and in-app prompts for respondent recruitment. Recruited participants were provided with a link directing them to the Qualtrics survey. We used nationally representative targeting and sampling; in addition, to ensure national representation and data quality, data were weighted post-testing using census data. Zip codes were collected and used to link responses to the U.S. Center for Disease Control's (CDC) EJ index (EJI)[71]. This index combines indicators of environmental burden, social vulnerability, and health vulnerability to reflect communities' cumulative burdens of environmental injustice (for list of indicators, see EJI Technical Documentation[72]).

National survey respondents ($N = 1633$) were first asked for basic demographic information, employment status, political identification, and concern about extreme weather, air and water pollution, and climate change. Questions on preferences used a four-point Likert scale[73]. Descriptive statistics of the survey sample are shown in Table 4.

Respondents were asked their perceptions of their communities' need for new industries to provide jobs and their trust in industry to deliver promised jobs. Those who selected "don't know" were pushed to consider their opinions. Participants were asked how much they had heard about DAC. Anticipating low prior awareness of DAC, we sought to increase the survey's likelihood of external validity by combining neutral language descriptions of DAC with images of various configurations of the technology (i.e. modular versus large-scale).

Conjoint design surveys have become a popular tool for social science research, especially where public policy is concerned, because they allow researchers to assess tradeoffs between policies, which are otherwise difficult to measure using traditional surveys formats[13,44,74]. We therefore used a conjoint analysis survey to collect national perceptions of DAC overall and, more importantly, to shed light on the various components of DAC policy and implementation that affect public and community perceptions. This design relies on a randomized balance design like the balanced overlap design developed by Sawtooth Software[75].

The forced-choice conjoint analysis experimental design assessed several of DAC's important socio-technical factors, which have been shown to influence public perceptions of infrastructure[76–78] (Table 1). Conjoint analysis is a commonly used method for understanding multidimensional preferences and has been validated against real-world behavior[79]. Attributes were selected following analysis of focus group discussions, which elucidated six attributes of concern and/or opportunity: funding source, level of community involvement, jobs creation, community reinvestment, energy sources, and CO_2 storage and transportation mechanisms.

Respondents were asked to make their selections as if the project were being proposed for their community. Given the wide price range for DAC, the scale of government subsidies currently available, and previous research showing that statements of cost tend to skew survey responses i.e.[39,50], cost was excluded as an attribute.

The minimum sample size for the survey was determined using the following formula:

$$\min = \frac{mc}{ta}$$

where m is a multiplier between 750 and 1000 (750 is considered more suitable for larger projects so it was used here), c the greatest number of levels per single attribute (five), t the number of tasks (thirteen), and a the number of alternative bundles presented (two). The power analysis tool developed by Lukac and Stefanelli[80] indicated a 99% predicted statistical power for our sample size of 1633 (with a 0% type S error and 1.02 exaggeration ratio) with our design.

Per the conjoint analysis format, Qualtrics randomly generated two "bundles" of attribute levels (i.e. for "Energy & heat source", the attribute, levels included "New or expanded fossil fuel energy" or "New or expanded wind/solar energy"), whereby each bundle contained one randomly selected attribute level per attribute. A broad array of attributes per category (i.e. energy & heat sources) were included in the policy choices to make them more realistic but were designed to be dichotomized for analysis per Zhirkov[81], as shown in the second column of Table 1. Attributes were independently randomized with uniform distributions so that each had an equal probability of being included in a policy package[81].

Participants were required to choose which bundle they preferred ("forced choice"). The task was repeated thirteen times. Each respondent therefore assessed 26 DAC "bundles", making the effective sample size 42,458 ($N = 1633 \times 26 = 42{,}458$)[44]. This forced-choice conjoint analysis approach was selected as it can imitate complex decision-making processes, including how individuals assess tradeoffs[34,39]. Full randomization of attribute levels allowed for nonparametric evaluation of their average marginal component effects (AMCEs)[82,83]. By facilitating participants' interaction with socio-technical components through repeated forced-choice exercises, we aimed to solicit deeper consideration of DAC. Respondents were provided definitions for geothermal energy and CO_2 storage mechanisms, as these terms are lesser known.

To draw causal conclusions from our ACME regression analysis, we made three assumptions, as laid out in Hainmueller et al. [83]. First, we assume that there's stability in a respondent's choices and no carryover effects from one bundle to the next. In other words, if shown the same sets of bundles twice, the respondent would choose the same bundle as the first time they saw both bundles. Second, we assume there are no profile-order effects, meaning that respondents' bundle choices aren't informed by bundles they've seen before. Finally, we assume that the bundles shown to the respondent are random in the sense that the possibility of any one bundle becoming a reality is random.

For non-conjoint sections, we produced three sets of models with the following outcome variables: level of support or opposition for DAC in the U.S., level of support or opposition for DAC in one's community, and the change in support or opposition for DAC when comparing between the U.S. and one's community. We used an ordinal logistic regression for analysis—a commonly used model for outcome variables with clear ordering (here, four-point Likert scale support or opposition toward DAC: "Strongly oppose", "Somewhat oppose", "Somewhat support", "Strongly support")[84–87]. To assess the adequacy of ordinal logistic regression, Brant's Test was used to check the proportional odds assumption and Variance Influence Factor to check for multicollinearity. The model included demographic controls at the individual level for sex, age, political party, education, and household income bracket, and additionally tested three hypotheses that emerged from focus group discussions:

H1: Support for DAC in or near one's community is likely driven, at least in part, by desire for workforce opportunities. This, in turn, both requires a perceived need for jobs and trust that jobs that are promised will be delivered.

H2: Support for DAC in or near one's community is informed by trust that the community will have the requisite trust and cohesion to negotiate favorable terms of a project, as represented by respondents' perceived ability to rely on their communities to solve problems.

H3: Support for DAC in general (at all scales), while initially partisan, may be modulated by a belief in anthropogenic climate change. This belief may counteract partisan anchoring for or against climate-related topics.

The model was tested for multicollinearity using variation inflation factors, with values under 5. Categorical variables were recoded numerically for ordinal logit model as follows:

Perceived need for jobs in one's community: "Little to no need" = 0, "Some need" = 1, "Large need" = 2, "Don't know" = NA;

Trust that new industries would deliver the quantity and/or quality of jobs promised ("When industries promise to deliver jobs in communities where they set up new facilities, which of the following best describes your expectations about how these industries do or do not deliver on their promises?"): "I expect industries will deliver both the number and quality of jobs they promise." = 2, "I expect industries will deliver the number but not the quality of jobs they promise." = 1, "I expect industries will deliver the quality but not the number of jobs they promise." = 1, "I expect industries will deliver neither the number nor the quality of jobs they promise." = 0, "Don't know" = NA.

Perceived ability to rely on one's community ("When I encounter a challenge, I rely on people in my community for help"): "Strongly disagree" = −2, "Somewhat disagree" = −1, "Somewhat agree" = 1, "Strongly agree" = 2, "Don't know" = NA;

Level of agreement that it is caused by human actions ("I believe Earth is experiencing rapid climate change caused by human activity": "Strongly disagree" = −2, "Somewhat disagree" = −1, "Somewhat agree" = 1, "Somewhat disagree" = 2, "Don't know" = NA.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The datasets generated during and/or analyzed during the current study are available in the Harvard Dataverse repository, https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi%3A10.7910%2FDVN%2FSU4MEG. https://doi.org/10.7910/DVN/SU4MEG.

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Author contributions
Celina Scott-Buechler designed the study, was responsible for data collection, and carried out the bulk of the analysis and manuscript writing. Bruce Cain contributed to the design of conjoint portion of the national survey and its analysis, and to manuscript writing. Khalid Osman helped with qualitative

data analysis and manuscript writing. Nicole Ardoin helped with qualitative data analysis, survey design, and manuscript writing. Catherine Fraser helped with focus group data collection and analysis. Grace Adcox fielded the national survey. Emily Polk helped with manuscript writing. Robert Jackson helped with manuscript writing.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Celina Scott-Buechler.

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