Perspective

Carbon Capture Technology through an Environmental Justice Lens

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Carbon dioxide (CO_2) levels in our atmosphere continue to reach new historic highs every day. In 2022, industry made up 30% of United States greenhouse gas emissions, including electricity end-use indirect emissions. Simultaneously, personal consumption expenditures increased by 9.2% in 2022 and continue to rise, indicating that there is an increasing need for decarbonization in production processes, with a tandem effort to combat overconsumption. One class of technologies that has garnered interest from researchers, policymakers, and communities is carbon capture. "Point source carbon capture" specifically refers to capturing CO_2 at its point of emission before it is released to the environment. However, as further scrutiny is put on carbon capture technology, it is clear that further research is needed and more options are necessary to ensure that our goal of reducing greenhouse gas emissions is not done without care. Carbon capture and sequestration or utilization have been touted as possible solutions for our growing demands, but present a range of health, safety, and environmental challenges, including siting concerns and possible leakages of pipelines or storage facilities. A relatively newer technology, reactive carbon capture (RCC), provides a potential pathway that minimizes some of those concerns. RCC converts CO_2 to valuable fuels and chemicals immediately after it is captured, eliminating the need for energy-intensive desorption from capture agents, as well as CO_2 storage and transport through pipelines. Thus, the entire process is contained at existing industrial plant sites, minimizing the span of environment and frontline communities that may be impacted by potential leaks and pollution. However, there are also a number of remaining challenges in RCC technology that must be addressed, alongside the need to decrease consumption, in order to be in accordance with environmental justice principles and make way for safe and effective technology adoption.

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I. INTRODUCTION

Carbon dioxide (CO_2) levels in our atmosphere continue to reach new historic highs every day. As of June 2024, CO_2 levels reached 427 ppm at the Mauna Loa Observatory in Hawaii [1]. In 2022, industry accounted for 30% of United States greenhouse gas (GHG) emissions, including electricity end-use indirect emissions. CO_2 contributes about 79% of the GHG effect, explaining why there is a concerted effort in the research community to address CO_2 specifically [2].

Simultaneously, personal consumption expenditures increased by 9.2% in 2022 and continue to rise, indicating that there is an increasing need for decarbonization in production processes, with a tandem effort to combat overconsumption [3]. Environmental justice communities (communities experiencing harm or who are at risk of harm due to environmental injustice and/or environmental racism) and organizations also indicate a need for centering the needs of marginalized communities, particularly those who have been and will continue to be most negatively impacted by climate change and environmental disasters [4,5]. Environmental injustice is defined as "the disproportionate environmental health risks placed on communities of color and communities in poverty, due to pollution, as well as unequal environmental protection laws, regulations, governmental programs, enforcement, and policies" [5–7].

One class of technologies that has garnered interest from researchers, policymakers, and communities is carbon capture. Direct air capture (DAC) and point source carbon capture are two subclasses of this technology, where "DAC" refers to capturing CO_2 from anywhere to reduce concentrations in air, while "point source carbon capture" refers to capturing CO_2 at a more concentrated emission point, such as at an industrial plant [8]. However, as further scrutiny is put on carbon capture technologies, it is clear that additional research is needed and more options are necessary to ensure that our goal to reduce GHG emissions is not

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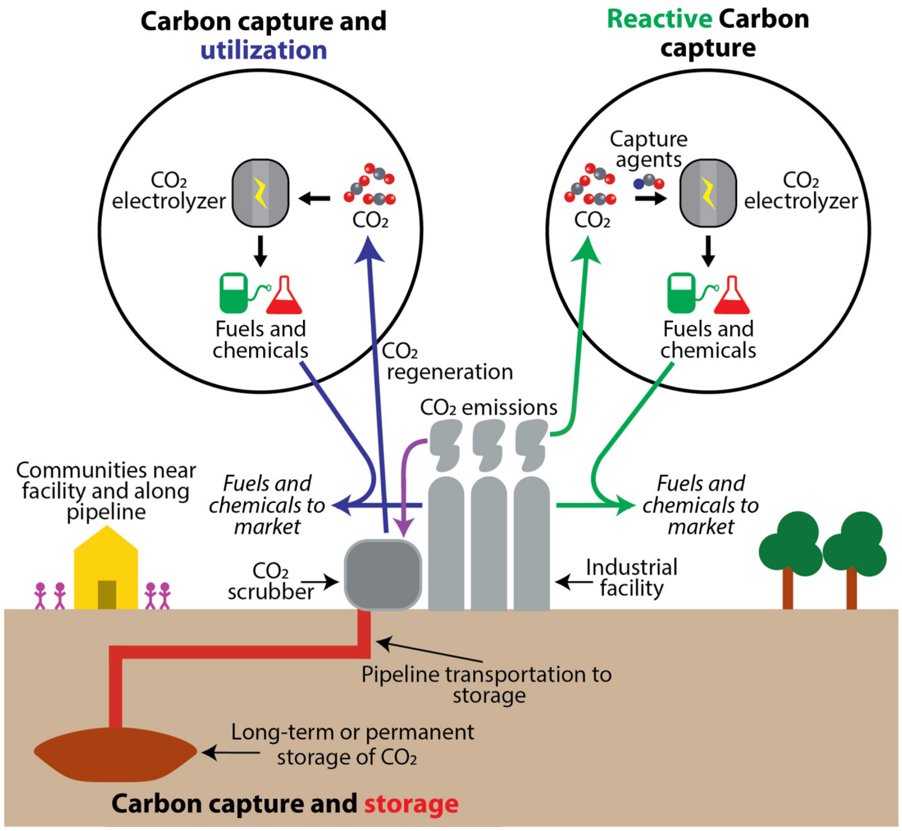

FIG. 1. Traditional carbon recycling technologies (i.e., CCSU) and RCC.

implemented without due consideration. Carbon capture and sequestration (CCS) and carbon capture and utilization (CCU) have been touted as possible solutions for our growing demands for resources, energy, and consumables, but come with respective sets of challenges and concerns surrounding impacts of their deployment, particularly related to the environmental, health, and safety impacts of short-term or long-term transportation, storage, or sequestration of CO_2. A somewhat newer technology, reactive carbon capture (RCC), is less well-developed technologically, but provides a potential pathway that minimizes concerns around CO_2 handling, as it immediately converts CO_2 after its capture. Figure 1 provides an overview of these three carbon recycling technologies.

Point source carbon capture isolates CO_2 during and/or after its production from the burning of fossil fuels, or other concentrated emission processes, to prevent its release to the atmosphere. There are three types of carbon capture: precombustion carbon capture, postcombustion carbon capture, and oxyfuel combustion [9]. In precombustion carbon capture, CO_2 is separated from gasified fuel; this is largely used in industrial facilities but is being developed for power plants as well. In postcombustion carbon capture, CO_2 is separated from the process exhaust stream. In oxyfuel combustion, a pure-oxygen environment is used rather than standard air, which allows fuel-burning exhaust to have a more concentrated stream of CO_2 [10].

Typically, captured carbon is separated from its capture agent, most commonly via energy-intensive temperature or pH swings, and is then either sequestered permanently as in CCS or temporarily stored and later used as in CCU [11]. In both cases, after separation from the capture agent, CO_2 must first be compressed and chilled to its fluid form. It is then transported via pipelines, ships, or trains to storage sites. Often, CO_2 is stored through injection into geological formations, or in former oil and gas reservoirs, deep saline formations, and coal beds. In CCU, the stored CO_2 is eventually released again in a controlled manner to be converted to valuable chemicals and fuels [12].

The benefits of carbon capture and sequestration or utilization (CCSU) center on the key benefits of carbon capture in general—CO_2 is not released to the atmosphere, therefore preventing an increase in GHG emissions and subsequent climate change effects. Facilities with CCS can capture 100% of their CO_2 emissions if they are using state-of-the-art technology [9]. Additionally, the touting of CCS promotes the idea that production processes can continue as usual with little change to other parts of the industrial process; that is, since industry can simply capture the emissions, there is an argument that there is no incentive to reduce the pollutants or toxicity of other parts of the process, or to reduce the emissions overall. However, this view largely ignores the risks and challenges associated with CCSU technologies.

Comparatively, RCC combines the steps for separation of CO_2 from its capture agent with the conversion to more valuable and benign species. RCC allows the utilization of captured carbon as in CCU, while eliminating the separate, energy-intensive step of dissociating CO_2 from its capture agent [11]. Instead, the captured CO_2 is immediately converted to a useful feedstock for use in the same industrial process or facility, or for use in a different process after transport of the new product. The use of RCC therefore eliminates the need for storage and transport of CO_2, among other necessities of traditional CCSU as detailed in the following section.

II. RISKS AND CHALLENGES OF CCSU

To evaluate CCSU as a technology that meets the expectations of multiple parties, including communities, policymakers, and researchers, we must consider the associated risks and challenges. Considering the overall process for CCSU, the compression of CO_2, after its separation from the capture agent, is the first hurdle to overcome as one considers the safety risks and engineering challenges associated with implementation of these technologies. Although there has been a strong effort to increase the safety and efficacy of compression of CO_2 for transportation, there is wide evidence that the parameters for transportation are highly case-specific. Factors such as inlet gas stream characteristics (e.g., temperature and pressure), end-point specifications for the CO_2 (e.g., geological storage or utilization), and operational transience (e.g., downstream compression fluctuations and dynamic energy demands) affect the design and performance of different transportation cases, meaning that there is no one-size-fits-all approach [13]. Subsequently, there is no uniform safety system that can be applied to all CO_2 transport systems, increasing the importance of risk assessments and vigilant safety controls. Centrifugal compressors are often used for elevation of the CO_2 stream pressure, and this requires a multistage system [13]. Power consumption of these compressors is a major factor when one is considering the overall efficiency of the system; pressure ratio, efficiency of the compressor, and inlet CO_2 stream temperature all affect the amount of power needed [14]. When CO_2 is being transported in its gaseous phase, a compressor must be used, while a pump can be used for liquid-phase CO_2, which is much more economical. However, liquefication requires the implementation of cooling systems to prevent CO_2 from reaching its low boiling point, which therefore increases the cost [15]. Impurities in the CO_2 stream can also affect the ability to compress CO_2 efficiently, which can lead to increased cost, time, and issues with leakage. CO_2 leakage issues at an industrial plant can greatly affect worker safety, as discussed further below.

As the next step in the overall process for CCSU, the transportation of CO_2 from its point of capture at an industrial plant or power plant to a storage facility poses many of the same challenges that natural gas transportation infrastructure implementation faces. The construction of new pipelines results in geological damage and potential routing through living communities, often low-income communities who do not have the political power to prevent such construction. Pipeline transportation also has technical and economic limitations, as well as risks associated with long-distance transportation of pure CO_2 specifically. Although CO_2 is neither toxic nor explosive in small concentrations, a high-volume leak can be a dire health hazard for both humans and animals. Aside from the chemical-related impacts, the high-pressure environment created in a pipeline to transport liquified CO_2 can also lead to devastating impacts due to explosions. Compressor stations along the route of a pipeline are an option to decrease the probability of a pipe bursting, but these stations are often placed in rural areas and can release chemical pollutants, leading to air quality levels below national standards [16]. These pollutants can also impact workers at compressor stations directly. As a result, pipelines have negative public perception due to their associated hazards, yet they are often deployed in spite of these concerns as a means to an end. This type of action is discouraging for communities who wish to combat climate change, but not at a further detriment to themselves and the environment [17]. Along with dangers associated with pure CO_2, the possibility of impurities in these streams introduces additional concerns. Treatment of CCSU CO_2 streams to remove impurities such as sulfur-based compounds, nitrogen oxides, and noncondensable gases (e.g., nitrogen, argon, and oxygen) leads to high financial costs for emitting industries, making this approach less desirable. However, these untreated CO_2 streams can affect pipeline or storage material integrity by inducing corrosion or scaling [18]. Furthermore, these impurities increase the hazards associated with possible leaks that would be relatively less severe with pure CO_2.

The long-term storage of CO_2 as in CCS also comes with a set of challenges, particularly considering the hazards of storage itself and the availability of storage space. There are widespread concerns regarding the safety risks associated with storage of CO_2 from numerous stakeholders. One risk is the possible leakage of CO_2 through channels connecting geological storage sites to other formations. Another risk is the possibility that CO_2 injected into the ground could induce faults, fractures, or earthquakes, increasing safety concerns for residents in these areas both due to the disasters themselves and due to increased risk of even greater leakage. There is also concern for the opposite relationship between these events;

that is, that natural disasters such as earthquakes could damage storage sites, leading to leakage of CO_2 to the environment [19]. There are differing opinions in the scientific community on the availability of storage sites as well. Some believe that ample sites exist domestically and internationally to account for CO_2 storage needs for centuries, while others conjecture that there is increasing uncertainty over sustainable injection rates for existing locations that stifle the pace and scale of CCS needs [20,21]. Nonetheless, it is clear that further exploration and tangible research is needed to determine the viability of CCS needs.

III. ENVIRONMENTAL JUSTICE CONCERNS

One can also consider the viability and holistic sustainability of a technology according to the needs of environmental justice communities by consulting the 17 Principles of Environmental Justice outlined at the first National People of Color Environmental Leadership Summit in 1991 (see the Appendix) [22]. One of the primary concerns from the public and environmental groups, at the aforementioned summit and continuing to the current day, regarding any carbon capture technology is the encouragement it gives to continuing our societal practices of overconsumption and overproduction. It is imperative to internalize this perspective as it is largely the communities who have experienced the harshest impacts of climate change who push for decreased consumption. This sentiment is expressed in the 17th principle of environmental justice, which specifically calls for us to “consume as little of Mother Earth’s resources and produce as little waste as possible.” Concerns revolve around the idea that business as usual is promoted by CCSU technology. In June 2023, the Climate Justice Alliance, a network of almost 100 grassroots organizations, called for the ceasing of CCSU technology, citing concerns with increased pollution by NO_x, the continuation of fossil fuel use, and the lack of trust in the benefits of these technologies truly bringing positive impact back to frontline communities [23]. This is in line with the 2nd, 3rd, 7th, and 12th principles, which all include elements of ensuring that environmental justice communities reap the benefits of climate technology and have fair access to resources. Some in the environmental justice movement and in climate change mitigation work also call for the adoption of “degrowth,” which involves the scaling down of production processes, shifting away from gross domestic product as a measure of prosperity, and a focusing of economic activity on human welfare [24]. Further, CCSU can interrupt other sectors of the economy, including agriculture; pipelines can travel through farmland, which can be detrimental to the agricultural industry, particularly when coupled with the possibility of leaks [25]. Leakage can contaminate groundwater and plant life, and can destroy soil quality—all impacting communities in areas with pipelines. The concern with potential ecological damage violates many of the principles, including the 1st, 6th, 8th, 12th, and 15th, which call for the cessation of ecological destruction and exploitation of land and living things. There are also concerns regarding the cost associated with CCSU [26]—namely, is the cost of such facilities and technology worth it when funding could alternatively be directed to programs that could directly benefit frontline communities?

These concerns mimic those associated with hydrogen technology as well: environmental justice groups have communicated their concern that hydrogen perpetuates the use of fossil fuels and overconsumption in general. However, a survey by the EFI Foundation in May 2024 found that 70% of surveyed environmental groups supported the use of green hydrogen (hydrogen generated through electrolysis), despite their concerns with the use of hydrogen generally [27]. Therefore, a similar parallel can be drawn between green hydrogen and RCC compared with their sibling technologies; surveys similar to the aforementioned survey would be helpful to better assess environmental groups’ opinions on RCC versus traditional CCSU technologies. Overall, it is clear that CCSU as it currently stands is not a substitute for addressing the causes and impacts of climate change by using a plethora of other approaches, including decreasing consumption, increasing implementation of renewable energy, and minimizing the use of polluting technologies.

IV. RELEVANT POLICIES

Several policies in the United States have been enacted federally and locally regarding CCSU implementation. The Inflation Reduction Act (IRA) of 2022, for example, updated the 45Q tax credit for the industrial sector to $85 for every metric ton of CO_2 captured and permanently stored in geological formations [28]. DAC, a leading CO_2 capture technology, also gained a higher incentive level of $180 per metric ton. The IRA also included a new capture threshold for credit-eligible facilities of 12 500 metric tons, reduced from 100 000 metric tons. The Infrastructure Investment and Jobs Act (IIJA) of 2021 also added $12.1 billion to carbon management technology, including regional DAC hubs, carbon capture demonstration project programs, carbon storage validation and testing, CO_2 transportation infrastructure, carbon capture large-scale pilot programs, and a carbon utilization program [29]. Now, in contrast to the broader trend of federal rollbacks of traditional clean energy incentives, H.R. 1, passed in July 2025, represents a significant policy shift by bolstering CCSU provisions [30]. H.R. 1 preserved the 45Q tax credit through to 2032 and standardized credit values at $85 per metric ton for CO_2 captured from industrial or electric generating sources and $180 per metric ton for DAC, regardless of whether the CO_2 is stored geologically, utilized, or used in enhanced oil recovery. As a result, H.R. 1 illustrates the priorities of the federal government by expanding CCSU incentives even as many other clean energy programs were curtailed, raising concerns about disproportionate prioritization of carbon capture over renewable energy deployment, particularly when considering the environmental justice implications. It is also important to note that much of the funds originally allocated to the IRA and IIJA are suspended or delayed, meaning that the full impacts of H.R. 1 and its subsequent executive order are not clear yet.

There has also been relevant legislation at the state level. Illinois state legislature passed the Carbon Dioxide Transportation and Sequestration Act in July 2024, which contains new regulations for CCS technology [31]. It applies a moratorium on the construction of new carbon capture sites until July 2026, unless the United States Pipeline and Hazardous Materials Safety Administration finalizes new safety rules before that date. It also mandates that carbon capture projects obtain permits that require safety monitoring during their operation and extend for at least 30 years after completion. Further, it requires that there is proof that the projects result in a net reduction of CO_2 emissions. This act was driven and supported by environmental, labor, and community groups in order to reduce the risks associated with CCS technology. This act demonstrates a concerted effort to push for technology that will reduce GHG emissions while enhancing its safety first. Other states have enacted a wide range of legislation regarding CCS technology, while some have no state-specific measures [32].

Unlike traditional CCSU technology, RCC has no relevant legislation except for that regarding carbon capture broadly. This is because the technology has not yet been sufficiently developed or demonstrated at a technology-readiness level that is suitable for implementation. Therefore, we currently have an opportunity to build productive RCC legislation both as research continues and once the technology is ready for on-the-ground use.

V. BENEFITS OF REACTIVE CARBON CAPTURE

We can compare traditional CCSU technology with RCC to better understand the benefits and risks associated with all carbon capture technology. Studies have shown that nearly 3.5 Gt CO_2 equiv. can be mitigated when CO_2-based feedstocks are substituted for fossil fuel, and cycling the carbon back into feedstocks further reduces the total emissions produced; this is a benefit seen by both sequential CCU and RCC [33]. Unlike CCU, however, RCC eliminates the energy-intensive middle step of CCU where CO_2 is typically desorbed from its capture medium and compressed for storage; instead RCC processes aim to directly drive conversion of the CO_2 as soon as it is captured. By avoidance of typical thermal release processes, there is high potential for energy savings when an RCC approach is used [11]. One study found that a theoretical RCC system has potential energy savings of 44% over traditional, sequential CCU when compared with a state-of-the-art-implemented CCU process [11]. Many of these studies rely on the assumption that all other processes for necessary fuels and chemicals will convert to carbon-free, zero-emission technology where possible, and that RCC would be used only for sectors, processes, or products that cannot be made completely carbon-free, due to the energy intensity and weight and volume limits of certain fuel applications, such as aviation, as well as the sheer abundance and reliance on carbon-based products, including for certain otherwise sustainable technologies, such as solar panels [34].

Cost considerations for CCSU and RCC technologies are critical for assessing their economic feasibility, although these costs will evolve as the technologies mature. Costs can be broken down into three main categories: capital costs, operating costs, and energy penalties. Capital costs encompass the initial investments needed to build and install the required infrastructure, such as reactors, sorbent systems, and retrofitting existing facilities. These costs are generally similar for both CCSU and RCC technologies [35–38]. Operating costs include ongoing expenses for running the system, such as labor, maintenance, and consumables. While operating costs can vary depending on the specific methods used, they tend to be higher for CCU and RCC compared with CCS due to the additional materials required for CO_2 conversion, such as catalysts [35,39–41]. "Energy penalties" refer to the extra energy needed to facilitate processes such as regenerating sorbents or compressing CO_2 for sequestration or utilization. RCC typically incurs a lower energy penalty than CCSU because it enables a simultaneous conversion and release process [37,39,42–45]. In contrast, CCSU systems face additional energy demands for compressing, transporting, and converting CO_2, resulting in higher energy penalties [37,46]. These distinctions in cost categories are crucial for determining the long-term viability and scalability of each technology.

Because RCC eliminates the steps of compression, transportation, storage, and re-release of CO_2, the myriad risks and challenges associated with these operations are not present. Several studies have assessed the life-cycle and technoeconomic implications of DAC and, to a lesser extent, RCC. One investigation developed a solid sorbent–based DAC process, emphasizing its potential for large-scale deployment, while underscoring that sorbent regeneration and material selection are critical to scalability [35]. However, regeneration can produce negative environmental impacts, and material sourcing may add a substantial footprint, even though the process could ultimately reduce atmospheric CO_2 levels. Another analysis examined different scenarios for DAC deployment, highlighting the influence of sorbent choice and energy demand [41]. While the study confirmed that DAC is highly energy intensive, it also noted that regeneration impacts differ by sorbent type, and that overall energy requirements are lower than those of conventional CCSU because DAC avoids compression and transportation steps. A separate evaluation compared amine-based and solid sorbent–based systems, pointing out that capturing CO_2 from ambient air requires significant energy due to its low atmospheric concentration [39]. The study authors stressed the need for efficient regeneration methods, noting that amine-based systems can produce harmful waste if unmanaged, whereas solid sorbent–based systems exhibit lower environmental impacts when regeneration energy is optimized. Finally, a study of solid sorbent–based RCC investigated a temperature-swing process for converting captured CO_2 into methanol, showing promise for cost-effective fuel production and environmental benefits from displacing fossil feedstocks [38]. Nonetheless, the life-cycle assessment highlighted trade-offs, as both CO_2 capture and methanol conversion entail substantial energy consumption due to pressure-temperature swings.

Implementation of RCC versus CCSU also eliminates the requirement for siting considerations beyond the industrial plant itself; installation of pipelines and injection of CO_2 into geological locations are both avoided, offering a notable benefit to vulnerable communities impacted by these activities. However, RCC does present a distinct set of challenges that still need to be addressed.

VI. RISKS AND CHALLENGES OF RCC

Various technical approaches to RCC at the fundamental research level are important to understand to determine promising routes for this technology. Recent advances in RCC research have often pursued one of two directions: thermocatalytic or electrocatalytic routes. One advantage of thermal approaches is the existence of thermal infrastructure; however, moderate temperatures and high pressures are necessary to drive the reaction, ranging from 80 to 155 °C and from 20 to 80 bar H2, respectively [11,47–51]. Both homogeneous and heterogeneous catalysts are explored in the thermocatalysis community to promote the capture and conversion steps of RCC. Electrocatalytic routes allow for homogeneous and heterogenous approaches as well. The process begins with activation by a reductive event, reaction of the catalyst with the captured CO_2, transformation of the CO_2 into products, and then final regeneration of the catalyst by another electrochemical step [11]. In electrochemical RCC, the primary challenge is competition with the hydrogen evolution reaction, which is promoted in the presence of a proton source such as water [52]. There are reports of substantial production of industrially relevant products with electrochemical RCC at the fundamental level, but a great deal of further research must be performed to better understand catalyst and capture agent interactions, relative energies of mechanistic steps, and feasibility of relevant species production [11,53–57].

Some of the other challenges associated with RCC are common for all carbon capture technology. For example, the carbon capture agents used for RCC and CCSU are generally in the class of amines. Although effective, amines can be highly toxic to human and animal health. For example, monoethanolamine (MEA) is commonly used due to its high reactivity and low cost. However, in sunlight, MEA along with other amines can undergo photooxidation, leading to degradation and the formation of compounds such as nitrosamines, nitramines, and amides. These compounds are toxic and carcinogenic for humans, even at low levels [58]. Furthermore, high levels of the principal amine can lead to high concentrations of particulate matter, especially PM2.5—amines can react with the environment to form fine particulate solids in some cases, particularly in plants with poor amine-scrubbing processes [59]. The potentially deadly nature of amine scrubbing for carbon capture technology has not gone unnoticed; the Center for International Law and 50 other organizations penned an open letter stating that CCS is not consistent with the Principles of Environmental Justice. Hence, it is clear that, even with the benefits RCC has over CCS and CCU, it is crucial that other potential hazards are not ignored during the relatively early stages of RCC research and policymaking. There are several methods to reduce or eliminate the possibility of amine contamination and leakage from CO_2 effluent. A water wash, for example, can recover volatile and aerosol amine to reduce the ultimate level of PM2.5 that is emitted [59]. The use of amines for RCC also conflicts with the sixth principle of environmental justice, which demands the cessation of the production of toxins and hazardous wastes. The eighth principle is also relevant, and calls for safe working environments for workers, although intentional and strong engineering controls at an industrial facility can greatly reduce risk.

There are also other pathways to replace amine scrubbing: for example, the use of (bi)carbonate-based and amino acid–based carbon capture agents [60]. Carbon capture systems with (bi)carbonate solutions are nontoxic and eliminate the risk of contamination from harmful byproducts typically associated with amines [61,62]. However, slower reaction kinetics and high energy demands of the desorption process remain significant challenges [63–65]. These costs could hinder large-scale adoption, but improvements in regeneration methods may reduce these barriers. Amino acid carbon capture agents, such as glycine, offer high CO_2 absorption rates and lower energy penalties compared with conventional amine-based methods [66–69]. They are also biodegradable, nontoxic, and stable for an extended period [70]. However, their regeneration still requires optimization to compete with traditional amine-based carbon capture. Hence, although (bi)carbonate-based and amino acid–based RCC offer safer pathways than amine-based RCC, there is a need for substantial research to achieve efficient operation at relevant scales.

Although RCC eliminates the need to compress and transport gaseous CO_2, there may still be a requirement to transport the fuels and chemicals produced by the process, particularly if there is no immediate demand for these products within the host industrial facility. The transportation of hazardous chemicals presents inherent risks [71,72], although the severity of these hazards relative to that of compressed CO_2 remains a topic of debate. Various government agencies within the United States, such as the Chemical Safety Board, which investigates the root causes of major chemical incidents, the National Oceanic and Atmospheric Administration, which monitors spills from maritime vessels, and the Department of Transportation, which tracks road-based spills, are responsible for overseeing hazardous incidents. These risks should not be disregarded in the assessment of RCC, and assessment of their impacts underscores the importance of situating industries that can utilize the fuels and chemicals produced from RCC in close proximity.

Some raw material processing methods for the production of solar panel components require the use of carbon-intensive technologies, indicating how there is still a need for such processes, even in the transition to greener technology [34,73]. RCC could be a method to continue these necessary processes to support the complete reduction of carbon emissions in other industries, such as the energy sector. This is in accordance with the 17th principle to minimize waste along with the third principle to be ethical, balanced, and responsible in uses of land and resources.

Lastly, as discussed previously, RCC can also unfortunately be implemented as another temporary solution to enable continued overconsumption. It does not halt the use of fossil fuels or similar technology, nor does it impede our rates of production and consumption. Most environmental justice groups lean toward rejecting any sort of carbon capture technology because of this implication and its violation of the Principles of Environmental Justice. However, it is also realistic to understand that society as a whole requires a drastic shift in culture in order to reduce consumption enough to make a difference in the amount of CO_2 that needs to be captured in the first place. Furthermore, since RCC is intended for implementation directly at current industrial sites, it is important to note that many such industrial sites are already located near vulnerable environmental justice communities. The Environmental Protection Agency's previously existent environmental justice screening and mapping tool (EJScreen) demonstrated this trend, and shows why even RCC does not solve all the issues of constraining emissions to a plant, since some level of external leakage is always possible, including unintentional leakages called "fugitive emissions" [74–76]. Importantly, these data are no longer available on the federal government–hosted website. The Environmental Data & Governance Initiative has since made EJScreen data available [76]. Figure 2 is taken from recovered data from EJScreen, and shows the strong correlation in Cook County, Illinois, between demographic index (i.e., low-income people and people of color) and a few industrial factors—namely, hazardous waste proximity, risk management plan (RMP) facility proximity, number of underground storage tanks and release sites in the proximity, toxic releases to air, and PM2.5 concentration [76].

However, the comparative infancy of RCC technology compared with CCSU technology means that there is an opportunity to develop engineering controls and critical policy before RCC is ready for implementation. Unfortunately, any technology that requires a large lead time for deployment becomes less valuable as the climate crisis worsens and the need for action becomes more urgent. There are currently no RCC facilities, while CCSU is increasingly deployed alongside industrial plants. It is important for policymakers and researchers alike to consider if CCSU technology can be effectively replaced or updated to enable RCC technology when the science is sufficiently developed to enable realization of the comparative benefits and positive environmental justice impacts. Otherwise, it may be impractical to completely transform the infrastructure again, and the costs may outweigh the very real benefits.

VII. WHAT IS THE PATH FORWARD?

In answer to the question "what path forward is best?" the only clear answer is that there is no perfect solution. What is more certain is that, as research continues in various areas of climate technology, emissions continually rise. Therefore, there is a dire need for the implementation of technologies that reduce and/or eliminate emissions to mitigate further environmental harm. Further, there is an increasing need for our society as a whole to reduce consumption. This begs a more complicated question—who is responsible for reducing consumption? Is it corporations, individuals, only wealthy individuals? The direct, yet difficult, answer is all of the above, but as we shift our culture and fight the overconsumption that plagues the United States and other countries today, it is crucial that we implement technology such as carbon capture *now* to reduce the emissions that are being produced daily. Unlike traditional CCSU technologies, RCC offers a pathway to prevent emissions from reaching communities and eliminates the need for transportation and storage of CO_2, instead isolating the associated vulnerabilities at an industrial site. However, there is a large amount of research and development that needs to be completed before RCC is

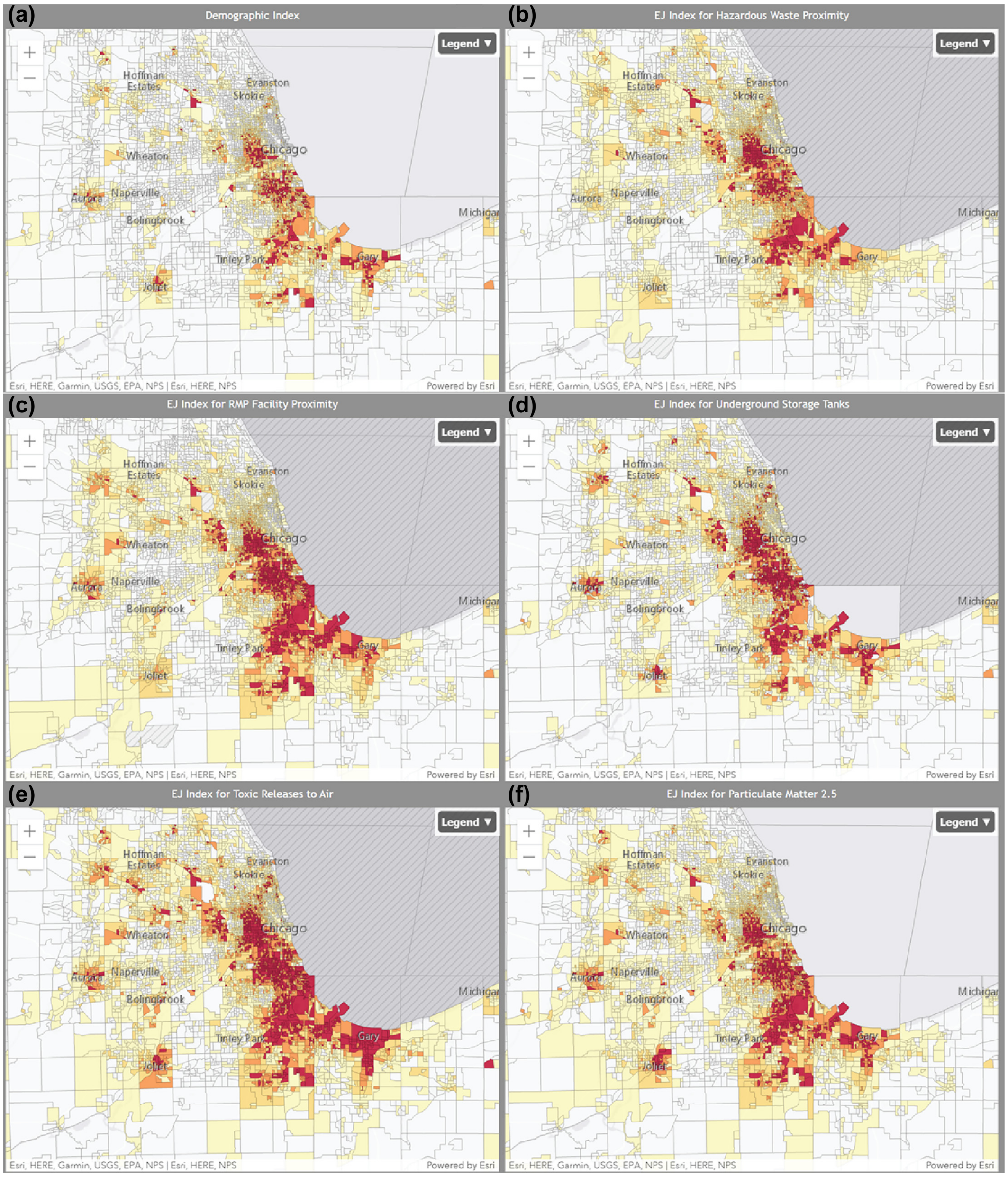

FIG. 2. Map of Cook County and surrounding areas in Illinois with environmental justice indicators generated from EJScreen [76]. Darker colors indicate higher concentrations or values of the associated metric. (a) Demographic index is the average of the percentage of low-income people and people of color in an area, (b) hazardous waste proximity measures how close people might live to a facility that handles hazardous waste, (c) RMP facility proximity measures how close people might live to an active facility with a required RMP (potential chemical accident management plan), (d) underground storage tanks measures how many underground storage tanks and release sites are near where people live, (e) toxic releases to air measures the average annual chemical concentrations in air weighted by the toxicity of each chemical, and (f) PM2.5 measures the potential exposure to inhalable particles 2.5 μm or smaller in terms of annual average concentration in micrograms per cubic meter. Definitions are taken from an archive of the Environmental Protection Agency's EJScreen index due to its removal from the website hosted by the federal government.

ready for widespread deployment. Fundamental research on the interactions of capture agents and catalysts, mechanistic steps of both thermocatalytic and electrocatalytic approaches, and ability to produce industrially relevant species is necessary to then move toward applied systems on a larger scale. In the long term, scaled-up systems will require careful consideration of safety, by-product species, and reaction conditions. It is essential to complete this work alongside efforts to decrease consumption and emissions overall. Centering environmental justice principles in all these discussions is crucial, in both research and policymaking spaces. Ultimately, RCC offers a pathway to continue supporting production of fuels, commodity chemicals, and materials that cannot be achieved through carbon-free or emissions-free processes and should be further studied and eventually implemented in parallel with other emergent sustainable technologies to decarbonize our industrial practices and transition to carbon-free and zero-emission processes. The combined effort from all sides will ultimately combat climate change and pave the way for a better future.

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DATA AVAILABILITY

No data were created or analyzed in this study.

APPENDIX: 17 PRINCIPLES OF ENVIRONMENTAL JUSTICE

The 17 Principles of Environmental Justice were generated by and adopted at the first People of Color Environmental Leadership Summit in 1991. The preamble and list of principles are as follows, reproduced from the Environmental Working Group’s website [22]:

“**Preamble** WE THE PEOPLE OF COLOR, gathered together at this multinational People of Color Environmental Leadership Summit, to begin to build a national and international movement of all peoples of color to fight the destruction and taking of our lands and communities, do hereby re-establish our spiritual interdependence to the sacredness of our Mother Earth; to respect and celebrate each of our cultures, languages and beliefs about the natural world and our roles in healing ourselves; to insure environmental justice; to promote economic alternatives which would contribute to the development of environmentally safe livelihoods; and, to secure our political, economic and cultural liberation that has been denied for over 500 years of colonization and oppression, resulting in the poisoning of our communities and land and the genocide of our peoples, do affirm and adopt these Principles of Environmental Justice:

1. Environmental justice affirms the sacredness of Mother Earth, ecological unity and the interdependence of all species, and the right to be free from ecological destruction.
2. Environmental justice demands that public policy be based on mutual respect and justice for all peoples, free from any form of discrimination or bias.
3. Environmental justice mandates the right to ethical, balanced and responsible uses of land and renewable resources in the interest of a sustainable planet for humans and other living things.
4. Environmental justice calls for universal protection from nuclear testing, extraction, production and disposal of toxic/hazardous wastes and poisons and nuclear testing that threaten the fundamental right to clean air, land, water, and food.
5. Environmental justice affirms the fundamental right to political, economic, cultural and environmental self-determination of all peoples.
6. Environmental justice demands the cessation of the production of all toxins, hazardous wastes, and radioactive materials, and that all past and current producers be held strictly accountable to the people for detoxification and the containment at the point of production.
7. Environmental justice demands the right to participate as equal partners at every level of decision-making including needs assessment, planning, implementation, enforcement and evaluation.
8. Environmental justice affirms the right of all workers to a safe and healthy work environment, without being forced to choose between an unsafe livelihood and unemployment. It also affirms the right of those who work at home to be free from environmental hazards.
9. Environmental justice protects the right of victims of environmental injustice to receive full compensation and reparations for damages as well as quality health care.
10. Environmental justice considers governmental acts of environmental injustice a violation of international law, the Universal Declaration On Human Rights, and the United Nations Convention on Genocide.
11. Environmental justice must recognize a special legal and natural relationship of Native Peoples to the U.S. government through treaties, agreements, compacts, and covenants affirming sovereignty and self-determination.
12. Environmental justice affirms the need for urban and rural ecological policies to clean up and rebuild our cities and rural areas in balance with nature, honoring the cultural integrity of all our communities, and providing fair access for all to the full range of resources.
13. Environmental justice calls for the strict enforcement of principles of informed consent, and a halt to the testing of experimental reproductive and medical procedures and vaccinations on people of color.
14. Environmental justice opposes the destructive operations of multi-national corporations.

15. Environmental justice opposes military occupation, repression and exploitation of lands, peoples and cultures, and other life forms.
16. Environmental justice calls for the education of present and future generations which emphasizes social and environmental issues, based on our experience and an appreciation of our diverse cultural perspectives.
17. Environmental justice requires that we, as individuals, make personal and consumer choices to consume as little of Mother Earth's resources and to produce as little waste as possible; and make the conscious decision to challenge and reprioritize our lifestyles to insure the health of the natural world for present and future generations.

Adopted today, October 27, 1991, in Washington, D.C."

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