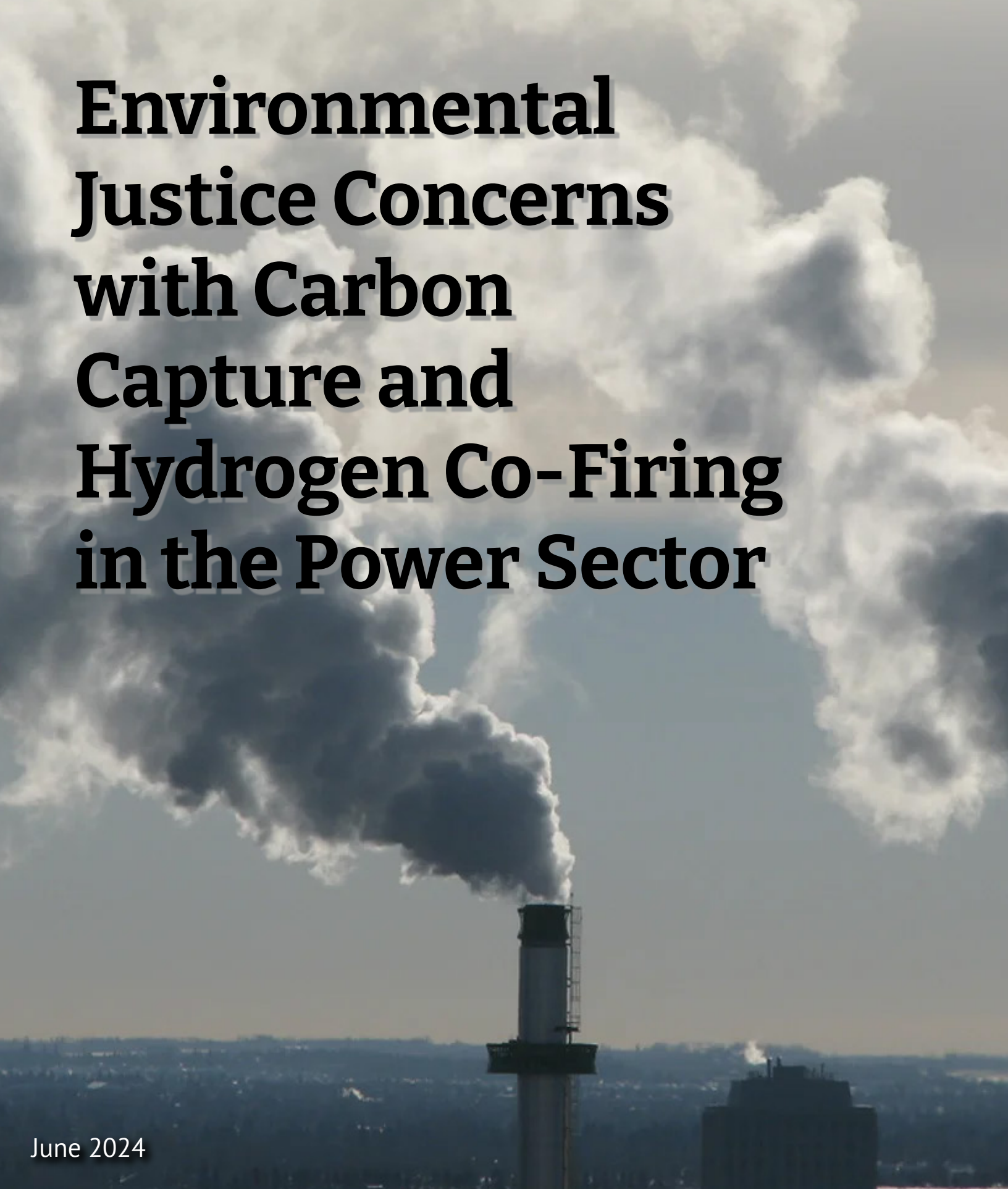

Environmental Justice Concerns with Carbon Capture and Hydrogen Co-Firing in the Power Sector

June 2024

THE NEW SCHOOL Tishman Environment and Design Center

KEAN UNIVERSITY John S. Watson Institute for URBAN POLICY & RESEARCH

Center for Earth, Energy & Democracy

NEW JERSEY ENVIRONMENTAL JUSTICE ALLIANCE NJEJA

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Summary

Current climate mitigation policies for the power sector are increasingly focused on technological approaches to "manage" carbon emissions, two prime examples being the deployment of technological carbon capture and storage/sequestration (CCS) and the burning of hydrogen-blended natural gas fuel. As much of the nation's energy infrastructure is located in low-wealth communities and Communities of Color, these carbon management approaches can have serious environmental justice implications. Yet there has been an absence of consideration of environmental justice in programs and policies that promote CCS and hydrogen deployment in the power sector. The following paper provides a summary of evidence demonstrating the threats posed by CCS and hydrogen co-firing to environmental justice communities in the United States. In synthesizing the best available data on equity, public health, and environmental risks, we find that the potential harm to communities already burdened by pollution warrants reconsideration of our investments and policies to promote carbon management. This caution is further underscored by the poor track record and questionable mitigation potential of these technologies. We consequently find that reliance on these technologies could precipitate a double injustice, both because of their direct impacts on already overburdened communities and because those communities are most vulnerable to the climate disasters that will ensue if we fail to implement climate mitigation grounded in proven renewable energy, regenerative, and just transition approaches.

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Table of Contents

I. Introduction

Industrial and energy systems contribute to pollution that overburdens environmental justice (EJ) communities in the United States. EJ communities, or low-wealth communities and Communities of Color, are disproportionately host to fossil fuel-derived power plants and other fossil fuel infrastructure (Declet-Barreto and Rosenberg 2022; Bridget, Ash, and Boyce 2021; Cushing et al. 2023; Fleischman and Franklin 2017), and are exposed to higher levels of air pollution (Boyce and Pastor 2013; Tessum et al. 2021; Cushing et al. 2023). The air pollution burden includes harmful "co-pollutants"—criteria air and water pollutants, such as fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), and sulfur dioxide (SO_2), mercury, a range of other hazardous air pollutants (HAPs), and volatile organic compounds (VOCs)—which are emitted alongside greenhouse gases (GHGs) like carbon dioxide (CO_2). Together, these pollutants contribute to disproportionately high pollution levels in EJ communities and a range of negative health outcomes (Lelieveld et al. 2015; T. Chen et al. 2007; Nitschke 1999; Guo et al. 2004; CDC 2021; Sundblad et al. 2004). Power plants and other fossil fuel infrastructure are not the only source of pollution in EJ communities. Other industries, land uses, and infrastructure contribute additional pollution in these neighborhoods, resulting in a large cumulative pollution load and cumulative health and environmental impacts in EJ communities (Morello-Frosch et al. 2011; Lam et al. 2022).[1]

There is evidence of a lack of attention to environmental justice issues with respect to energy projects and planning. Examples of this are the scarcity of accessible venues to meaningfully participate in energy planning and implementation (Lenhart and Fox 2022; Triedman et al. 2021), insufficient transparency in project development (Sierra Club 2023; Bioret, Zhu, and Krupnick 2023), the framing of community burdens as "benefits," (WHEJAC 2023) and the continued siting and development of fossil fuel infrastructure in EJ communities (Sheats et al. 2023). This inattentiveness to EJ in the energy sector has been most recently exemplified in the federal government's investments in "carbon management" as the way to approach climate change mitigation.[2] It postulates that the power sector's GHG footprint can be reduced

1 While there are many overlapping definitions of cumulative impacts, one that has been used by the New Jersey EJ community is "The impacts and risks caused by multiple pollutants both individually and by their interactions with each other and with any social vulnerabilities that exist in a community. The pollutants are usually emitted by multiple sources located in a community." For example, see NJEJA 2021.

2 As described by the WHEJAC, "'carbon management' is an umbrella term that can blur and include diverse technologies, carbon reduction strategies or low/non-carbon fuels" (WHEJAC, 5). WHEJAC has

through capturing and storing the CO_2 emissions of fossil fuel power plants and/or through burning hydrogen-blended natural gas, as a purported lower-carbon fuel, for power generation (referred to as "hydrogen co-firing") to ease the transition to renewable energy sources and help achieve net zero goals.

One recent example of the federal government's adoption of carbon management as a key climate mitigation strategy for the power sector is the U.S. Environmental Protection Agency's (EPA) 2024 power sector GHG rule for new gas and existing coal-fired electric generating units (EGUs) (EPA 2023), which upheld carbon capture and storage (CCS) as the best system for emissions reduction (BSER). As pointed out by various commenters in the public comment period, the proposed rule (EPA 2023) did not adequately consider the public health and cumulative impacts that fence-line communities will face from such technologies—even while it recognized that these technologies may lead to increased emissions of harmful co-pollutants, such as NO_x (TEDC et al. 2023; CEG et al. 2023). Originally, the proposed rule also considered hydrogen co-firing as BSER and covered existing natural gas EGUs (EPA 2023). Following the comment period, the EPA announced that it would reconsider the rule's treatment of existing natural gas EGUs (EPA 2024b) and ultimately removed requirements for existing natural gas EGUs from the final rule. This reconsideration was viewed by environmental justice advocates as an opportunity to better regulate natural gas EGUs in the power sector (Shepard et al. 2024). The EPA also removed hydrogen co-firing as a BSER for new natural gas EGUs (Dlouhy 2024) in its final rule (EPA 2024).

Notably, the White House Environmental Justice Advisory Council's (WHEJAC) Carbon Management Workgroup has voiced serious concerns about the EJ implications of carbon management technologies, and in fact has called for cessation of the implementation of various carbon management technologies and associated programs, including CCS and hydrogen co-firing (WHEJAC 2023, 2). Other EJ groups have expressed similar concerns (see, e.g. CEJA 2023; TEDC 2023). In reaching its recommendation, the WHEJAC observed that these technologies have "serious impacts on communities affected by environmental injustice" and have not been "proven as safe and effective alternatives to non-carbon-based energy sources" (WHEJAC 2023, 4). The WHEJAC stated that it "is surprised at how environmental justice concerns related to safety, public health, environmental risks, cumulative impacts, and efficiency are unaddressed, addressed inefficiently, or addressed haphazardly

highlighted that the lack of clarity in terminology and definitions is an obstruction to understanding the risks associated with the different approaches, as well as to oversight and accountability (WHEJAC, 7). We offer working definitions for purposes of this paper in Section II below.

by the federal government and other proponents of carbon management. This surprise warrants the aforementioned pressing recommendation[]" (WHEJAC 2023, 16–17).

Overall, this paper provides a summary of the evidence of the EJ concerns related to CCS and hydrogen co-firing in the power sector, and advances nascent scholarship on the risks posed to EJ communities across the United States by the increased investments in carbon management as a climate mitigation strategy. The paper begins with a brief overview of CCS and hydrogen co-firing in Section II. Section III proceeds to highlight the health and justice concerns triggered by the deployment of CCS and hydrogen co-firing at power plants, summarizing available evidence on the health, safety, and environmental risks. Finally, Section IV provides a brief overview of evidence that casts doubt on whether these technologies can deliver efficient or effective climate mitigation.

Overview of Environmental Justice (EJ) Concerns with Carbon Capture and Storage (CCS) and Hydrogen Co-firing in the Power Sector

Substantial evidence suggests that the implementation of CCS and hydrogen co-firing in the power sector will contribute to pollution at every stage of their deployment, and that these impacts can exacerbate the burdens that communities hosting fossil fuel infrastructure already face. While proposals and pilot projects that utilize CCS and hydrogen largely fail to quantify and track potential harm to communities, there are indications that there will be some level of increase in pollution burdens, as has been acknowledged in the academic literature and by the U.S. Environmental Protection Agency. From an EJ perspective, the imposition of additional risks and burdens on low-wealth communities and Communities of Color that are already subjected to multiple environmental hazards and social stressors is unacceptable.

To summarize some of the most pressing health and justice concerns, CCS and hydrogen co-firing can increase harmful co-pollutant emissions, both from the additional energy used to power the CCS process and from the combustion of hydrogen during co-firing. CCS can contribute to additional risks along the supply chain by producing harmful chemical by-products, presenting health and safety risks from pipeline leaks and explosions during CO2 transport, and posing a risk of CO2 leakage when stored underground. Hydrogen co-firing can also add to co-pollutant emissions during hydrogen production and combustion of hydrogen-blended fuels, and add to methane emissions during hydrogen production, transport, and use. Heightening concerns, the existing regulatory environment is demonstrably deficient to protect EJ communities. Even though these many risks have been identified, sufficient analysis has not been conducted to fully understand the potential effects on EJ communities.

The EJ concerns named above are enough to warrant reconsideration of carbon capture and hydrogen co-firing in the power sector. However, additional evidence and a troubling track record raise doubt that these strategies will even deliver effective climate mitigation benefits. Allowing the fossil fuel industry to use CCS and hydrogen to avoid a real transition to clean energy is itself an EJ concern, as the perpetuation of fossil fuels will further harm EJ communities, whose members will be among those suffering ‘first and worst’ from the impacts of climate change.

II. Brief Overview

A. Carbon capture and storage (CCS) overview

Carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) refer to a suite of technologies whereby carbon dioxide (CO_2) is captured, typically from a large point source, separated at the point of combustion, and transported on- or offsite for use or long-term storage.[3] In addition to being implemented to address the CO_2 emissions of chemical, hydrogen, fertilizer, and ethanol production and natural gas processing, carbon capture can be used in the power generation sector at natural gas and coal-fired facilities (Jones and Lawson 2022). Carbon capture is therefore different from carbon dioxide removal (CDR), which generally refers to the removal of CO_2 that is already in the atmosphere, but both are part of general approaches to "carbon management" (Figure 1). While this paper explicitly focuses on CCS/CCUS, CDR techniques such as direct air capture (DAC) and bioenergy with CCS (BECCS) share similar environmental justice concerns, such as GHG co-pollutant emissions and public health impacts. DAC and

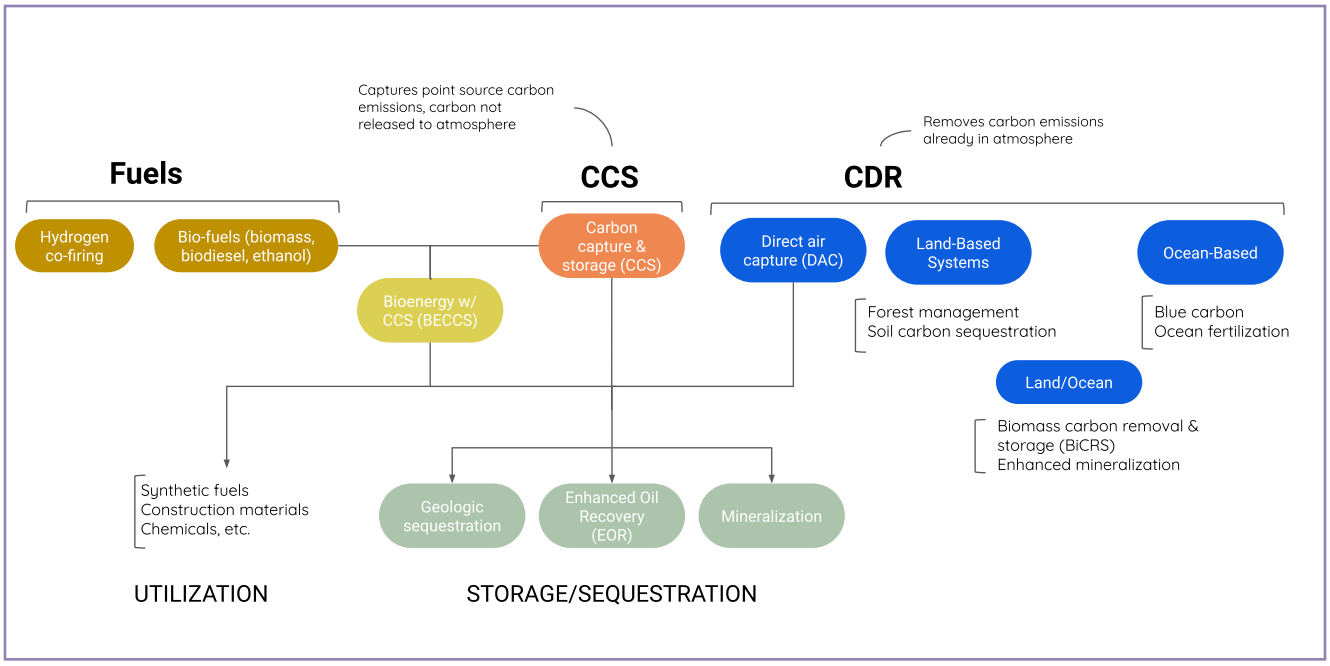


Figure 1. "Carbon management" approaches

[3] For the remainder of the paper, we will refer only to the term "CCS," as we do not detail the myriad risks associated with various uses of CO_2. The paper only discusses enhanced oil recovery (EOR), one of the principal uses of captured CO_2, in Section IV.

BECCS were also among the technologies for which the WHEJAC urged the halting of all activities and associated programs (WHEJAC 2023, 2).

The carbon capture process has three main stages. In the context of the power generation sector, these are: 1) capture of CO_2 from the power plant, 2) transport of CO_2 as a supercritical fluid, liquid, or gas, and 3) use or storage of CO_2 (Figure 2).

1) Capture: In the capture stage, the three main types of capture processes for power plants are pre-combustion, oxyfuel combustion, and post-combustion. In pre-combustion, the primary fuel (e.g., coal, natural gas, or biomass) must be gasified and then separated into streams of CO_2 for storage and H_2 for fuel. Pre-combustion capture is still in the early stages of development and not commonly used in existing power plants (Gonzales, Krupnick, and Dunlap 2020). In the oxyfuel process, CO_2 is separated from flue gases (the combustion exhaust) after the fuel has been combusted in pure oxygen, creating water and CO_2. Post-combustion, whereby CO_2 is separated from flue gases after the fuel has been combusted in air (Gonzales, Krupnick, and Dunlap 2020), is the most common method used in power plants today. It has also received the most attention to date because it is easier to retrofit existing plants for post-combustion compared to other methods (Chai, Ngu, and How 2022).

For post-combustion separation of CO_2 from the fuel source, there are currently four main processes that can be used: (1) chemical absorption, (2) adsorption, (3) membrane separation, and (4) cryogenic distillation (Chai, Ngu, and How 2022).[4] Various chemicals have been studied as candidates for chemical absorption, and they vary in terms of their CO_2 absorption efficiency, absorption capacity, energy requirements, and environmental risks and effects (Chai, Ngu, and How 2022). In the process of capture, the most researched and implemented technique for separating CO_2 relies on chemical-based absorption, with primary amines being the most common chemicals used (Chai, Ngu, and How 2022). Although chemical absorption has been the most researched and implemented of the four separation methods, a 2022 paper that comprehensively reviewed chemical absorbents notes that the absorbents under consideration "are not ready yet for large-scale applications…." (Chai, Ngu, and How 2022). Adsorption is a similar process requiring a chemical reagent to trigger the binding of CO_2 to that chemical; however, these chemicals typically are

[4] Absorption involves the mass transfer of particles into another material (one substance absorbing another); adsorption is the adhesion of particles onto the surface of a substance (Chai, Ngu, and How 2022).

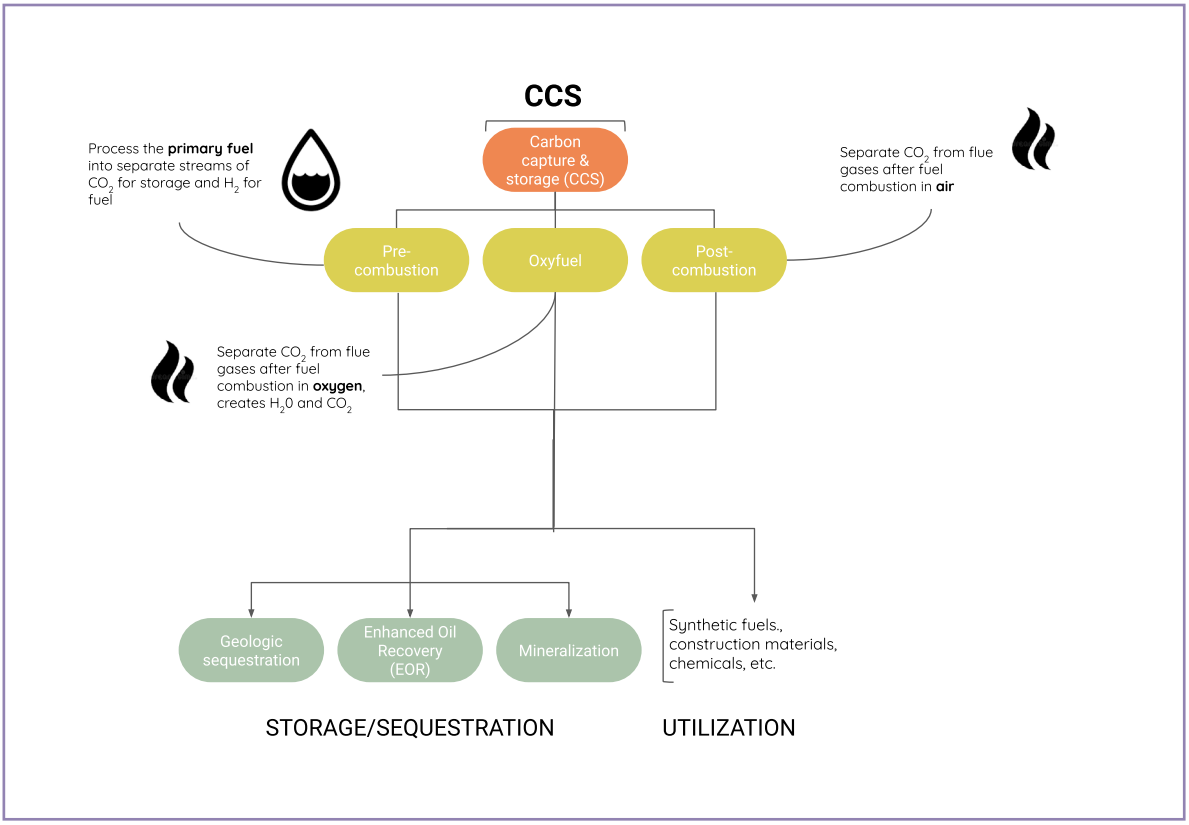


Figure 2.
Carbon capture processes

unable to 'hold' much CO_2 or select for CO_2 efficiently (Chai, Ngu, and How 2022). The other two techniques, cryogenic distillation and membrane separation, have also faced barriers in working at scale due to the conditions required of the flue gas and intensive energy input (Chai, Ngu, and How 2022).

2) Transport: With respect to CO_2 transport, power generation facilities may be located far from suitable geologic storage sites, such as saline aquifers, unmined coal beds, and depleted gas or oil reservoirs that meet capacity, injectivity, and containment conditions (Ajayi, Gomes, and Bera 2019). In these cases, CO_2 will need to be transported offsite, primarily via pipeline. Currently, the United States has around 5,150 miles of CO_2 pipelines, making up around 2.2% of all hazardous liquid transmission pipelines nationwide (Kuprewicz 2022a). Princeton's Net-Zero America study estimated that by 2050 more than 60,000 miles of new CO_2 pipelines may be needed to meet climate targets (Larson et al. 2021).

3) Storage/Use: Following capture and transport, CO_2 can be used or stored. Uses for CO_2 include the production of synthetic fuels, construction materials, and such chemicals as ethylene, propylene, methanol, butadiene, and polyvinyl chloride. CO_2 can also be injected underground to obtain trapped oil, a process known as enhanced oil recovery (EOR). Currently, most captured CO_2 is used for EOR. In fact, approximately 70% of CCS projects globally and 85% in the United States take advantage of EOR (Zapantis et al.

2022).[5] One storage method is geological sequestration, whereby CO_2 is stored underground. Typically, it is first pressurized into a liquid and then injected into porous rock formations in geologic basins. Another storage method is mineralization, whereby CO_2 reacts with calcium and magnesium in rocks to form solid carbonate minerals (Kelemen et al. 2019). As discussed in Section IV.B, the level of permanence with respect to the different types of CO_2 storage is uncertain, though storage would have to be effectively permanent for the climate mitigation "benefit."

B. Hydrogen co-firing overview

There are three main components to consider in examining the use of hydrogen fuel in the power sector: 1) production, 2) transport/storage, and 3) use.

1) Production: The vast majority of hydrogen produced today is fossil fuel-based hydrogen, which is derived from the combustion of a hydrocarbon fuel source, namely coal or natural gas (IEA 2019). Steam methane reforming (SMR), a process used to obtain hydrogen from natural gas by reacting the gas with steam in a series of chemical reactions (Barelli et al. 2008), accounts for almost 75% of hydrogen production worldwide (Longden et al. 2022). Estimates show that SMR is also the predominant method for producing hydrogen in the United States (Muradov 2015; Barelli et al. 2008). Gasification is another process used to obtain hydrogen from coal. Hydrogen produced via SMR and gasification is sometimes referred to as "gray hydrogen", or "blue hydrogen" when these methods are coupled with carbon capture of some of the CO_2 from the process (Midilli et al. 2021).

There has also been increasing interest in the production of so-called "green hydrogen,"[6] which uses renewable energy sources to power a process called electrolysis that uses electricity to separate hydrogen from water (M. Yu, Wang, and Vredenburg 2021). However, producing hydrogen via electrolysis requires substantial water and energy inputs, and it represents only an estimated 0.1% to 2% of overall hydrogen production due to its high costs (IEA 2019). Given its infancy, green hydrogen production is not the focus of this paper, though we provide some additional considerations in a breakout box on page 37.

2) Transport/Storage: Where hydrogen demand is less, it is transported via on-road vehicles (DOE EERE, n.d.). The primary proposal for transporting

[5] While the vast majority of U.S. CCS projects in the "advanced development" stage are slated for dedicated geological storage, the feasibility and accuracy of these designations are yet to be determined.
[6] There are multiple, varying definitions for green hydrogen (Velazquez Abad and Dodds 2020).

hydrogen for applications and regions with substantial and consistent demand is via pipeline (DOE EERE, n.d.). However, there are currently only 1,500 to 1,600 miles of pipelines dedicated to hydrogen transport, in comparison to the 300,000 miles of onshore natural gas transmission pipelines and 2.3 million miles of natural gas distribution pipelines in the country (Kuprewicz 2022b). The transport of hydrogen (by itself or blended with natural gas) is considered one of the technological challenges associated with hydrogen buildout, with the Department of Energy (DOE) describing several areas in need of work, including developing standards for blending hydrogen into natural gas pipelines, identifying when natural gas infrastructure can be repurposed for hydrogen, and determining when new infrastructure must be built (DOE 2023). These challenges stem at least in part from the fact that hydrogen or gas mixtures containing hydrogen are more difficult to move around compared to natural gas, as they have higher susceptibility to combustion, increased tendency to leak because of hydrogen's smaller molecule size, and greater dispersion when released (Kuprewicz 2022b).

Along the various stages of the supply chain, hydrogen is stored in insulated liquid tanks or gaseous storage tanks (DOE, n.d.-b). There is also the potential for bulk hydrogen to be stored underground, for example in salt or rock caverns (DOE, n.d.-b). Liquid storage tanks are most common for large quantities of hydrogen; this method requires venting gaseous hydrogen buildup either by releasing it into the atmosphere or recompressing it to store (DOE, n.d.-a; n.d.-b).

3) Use: For power generation, hydrogen is added to natural gas and used, or co-fired, as a blended fuel. The DOE has maintained that the blend is a low-carbon fuel that power plants can burn in place of natural gas alone (DOE 2020b). As of 2023, blends of 20% to 30% have been tested, and the federal government seems to assume that blending at even higher percentages (upward of 90%) will be achievable (EPA 2023, 33305). Combustion of such high-hydrogen blends requires substantial retrofits at existing natural gas facilities, which is also under research and development (EPA 2023; DOE 2023).[7]

[7] Though beyond this paper's focus, there are also other uses of hydrogen in industrial processes, such as in the production of ammonia (Longden et al. 2022), which is a primary component of fertilizer, and within the oil and gas industry for petrochemical processes, such as desulfurization and hydrocracking (Szabo 2021). There have also been proposals for hydrogen blending where the blend is transported directly via pipelines to homes and businesses for heating and cooking (Howarth and Jacobson 2021). Additionally, there has been discussion about the use of hydrogen for "hard to decarbonize" sectors that are beyond

III. Health and Justice Concerns with CCS and Hydrogen Co-firing

We found substantial evidence suggesting that CCS and hydrogen co-firing will contribute to pollution at every stage of their deployment, and that these impacts will in all likelihood exacerbate the burden of pollution that communities hosting fossil fuel infrastructure currently face. The situation raises significant environmental justice concerns, as many of these fence-line communities are low-wealth communities and Communities of Color that are already facing cumulative impacts of multiple environmental hazards and social stressors (Morello-Frosch et al. 2011). The following section outlines several key types of impacts from deploying CCS and hydrogen co-firing in the power sector, including co-pollutant emissions, use of harmful chemicals, contamination of water sources, and pipeline explosions.

A. CCS

Air co-pollutants and chemical contamination at the CO_2 capture phase

For coal and natural gas power plants that already produce harmful levels of GHG co-pollutants, the fuel required to power the CCS process will contribute additional co-pollutants that impact local air quality (Yuanyuan Zhang, Zhang, and Zhang 2013). First, there are co-pollutant impacts associated with the extraction, production, transport, and storage of coal and natural gas used to power the CCS process (Donaghy et al. 2023), as described in more detail in Section B.1. Second, there will always be an energy penalty or parasitic load due to the energy required to power a carbon capture facility, which will result in increased co-pollutant emissions at the site of combustion compared to a facility without carbon capture. In the power sector, the impact of CCS on the emission of co-pollutants varies based on the type of capture process (pre-, post-, or oxyfuel combustion) and the plant type/fuel source

the scope of this paper. Even for those applications, a number of conditions have been raised as requisites to mitigating EJ concerns, as put forth by the California Environmental Justice Alliance's "Environmental Justice Equity Principles for Green Hydrogen in California" (CEJA 2023).

(natural gas combined cycle, coal, gas, or integrated gasification combined cycle) (EEA 2011). However, across all capture processes and plant types, NO_x, $PM_{2.5}$, VOCs, and ammonia (NH_3) will generally increase, typically in proportion to the additional fuel combusted to power the CCS process (EEA 2011). A notable exception, for coal plants in particular, is that NH_3 will increase significantly more than that, by a factor of ten to twenty-five (EEA 2011; van Horssen et al. 2009). Coal plants that do not build a separate cogeneration facility and use coal power for the carbon capture facility will have even higher co-pollutant emissions per unit of energy used.

While certain co-pollutants may be controlled—for example, in amine-based solvent separation, most SO_2 will need to be removed for the process to work (EEA 2011; D. Wang et al. 2022)—the deployment of carbon capture can yield more harmful air pollution and associated risks for adjacent or downwind communities overall.[8] (See, for example, the breakout box on Petra Nova below.) Proponents of CCS argue that it will reduce criteria air pollution at capture sites because the retrofits would require implementing higher pollution control standards for facilities (see, e.g., EFI 2023, 149). However, EPA's current NO_x standards for new gas plants have not been reviewed in 16 years. As such, new gas plants are not required to install the most updated NO_x emission control technology. In 2022, 38% of coal-burning power plants nationwide still lacked modern NO_x controls, and even power plants equipped with controls are not required to operate the control consistently and effectively (Filonchyk and Peterson 2023). In light of this, communities adjacent to power plants with CCS are likely to experience increases in air pollution as a result of CCS deployment, especially absent any additional required pollution control upgrades.

The co-pollutants generated from powering the CCS process, such as $PM_{2.5}$, NO_x, which includes nitric oxide (NO) and nitrogen dioxide (NO_2), VOCs, and NH_3, all have documented associations with harmful health outcomes. To name a few, $PM_{2.5}$ has been linked to respiratory illness and cardiovascular disease (Lelieveld et al. 2015), and NO_2 has also been linked to respiratory illnesses, such as asthma (T. Chen et al. 2007; Nitschke 1999), and is also a precursor for both PM and ozone (EPA 2016c). Health effects associated with VOCs include acute and chronic respiratory issues, neurological toxicity,

[8] According to a 2022 study, most, but not all, of the SO_2 should be removed: "An International Energy Agency research report suggested that the amine-based CO_2 capture process should limit the SO_2 concentration to less than 10 ppmv in flue gas (11). Therefore, highly efficient flue gas desulfurization (FGD) technologies have become a basic requirement for postcombustion CO_2 capture" (D. Wang et al. 2022).

and cancer (Guo et al. 2004). NH_3 is a poisonous substance that, when concentrated, can corrode human tissue and have acute respiratory effects (CDC 2021; Sundblad et al. 2004). EJ communities in the United States already face higher rates of asthma and other chronic illnesses from indoor and outdoor air pollution (Tessum et al. 2021; Richardson et al. 2020), and the buildout of CCS concentrated around EJ neighborhoods can exacerbate these existing disparities.[9]

Moreover, the amine-based solvents generally used to separate CO_2 have been found to exhibit various harmful effects in the environment, with multiple pathways by which people could get exposed. These solvents are also potential carcinogens, may contaminate drinking water, and have adverse effects on aquatic life (EEA 2011). One peer-reviewed study found that ecotoxicity effects on freshwater and terrestrial ecosystems may increase due to monoethanolamine (MEA), a primary amine that is the most used chemical for CO_2 separation to date and has a toxicity comparable to that of cyanide (Supekar and Skerlos 2015; Veltman, Singh, and Hertwich 2010). In a 2022 letter to the White House Council of Environmental Quality (CEQ), the Environmental Defense Fund warned that the risks associated with nitrosamines are not fully understood or presently included in regulatory and permitting risk-based requirements, but that they "may pose serious hazards to workers and the public near capture facilities" (Anderson and Saunders 2022). Marginalized communities in the United States are already exposed to contaminated water systems, with a review of the literature focused on EJ and water contamination finding that all but one study reported some level of elevated contamination (Karasaki et al. 2023). Several studies have also found that the emission of amine-based solvents used to separate the CO_2 could cause smog formation, another exposure pathway (Pehnt and Henkel 2009; Zapp et al. 2012). Exposure to smog has been linked to respiratory illnesses, cardiovascular disease, neurological complications, cancer, and low birth weight (Javed et al. 2021). Studies have also documented how worsening climate change impacts may contribute to oil and hazardous contaminant spills, (Dong et al. 2022) and worsen them (Flores et al. 2021), which may be another exposure pathway and area of concern for harmful amine-based solvents.

Even though the solvent can be re-used in the capture process,

[9] In a forthcoming paper, we will add to this review of the evidence by presenting original research findings from a proximity analysis of 1) planned CCS facilities and EJ communities and 2) coal and natural gas plants implicated by EPA's proposed power sector rule and EJ communities, and assess both in relation to existing environmental stress in these areas.

degraded amine waste is a by-product. The waste is hazardous, and it includes chemicals like ammonia, heat-stable salts, which can cause corrosion (Tanthapanichakoon, Veawab, and McGarvey 2006), organic acids that can affect aquatic life (Salim 2021), and aldehydes (e.g., formaldehyde) (Salim 2021; Chandan et al. 2014; Vevelstad et al. 2022). It also contains nitrosamines, which have long been considered carcinogenic (X. Chen et al. 2018; Fostås et al. 2011) and can enter the environment via stack emissions or disposal of spent solvents (K. Yu, Mitch, and Dai 2017). Degradation products can result in hazardous exposures. Some of them are unregulated and can end up in a facility's wash water. For waste that is disposed of in a landfill, which is slow to biodegrade, or waste that is incinerated, additional environmental (Sexton et al. 2016) and health harms can be expected. Research going back decades has found that EJ communities are disproportionately sited near hazardous waste sites (United Church of Christ 1987; Bullard et al. 2007; Mohai and Saha 2007). Any additional harmful material from CCS waste products at these sites will contribute to increased burden in EJ neighborhoods.

While there has been research to examine other chemicals besides amines for use in chemical-based absorption, these efforts are inchoate. The tradeoffs in the chemicals' properties are the general problem. For example, certain chemicals can be less volatile, less flammable, and less harmful for the environment, but they have other issues regarding absorption capacity, energy requirements, cost, and other factors depending on the chemical (Chai, Ngu, and How 2022). A 2022 review found that none of the chemicals among the numerous substances that are supposed candidates for chemical absorption are ready to be deployed at a large scale (Chai, Ngu, and How 2022). It notes that research to experiment with creating hybrid chemicals to make a more well-rounded absorbent is "still in its infancy." The review pointed to a number of significant challenges, including a lack of data on economic and environmental performance of carbon capture operations and the poor carbon capture capabilities of most chemical absorbents (Chai, Ngu, and How 2022, tbl. 5).

Petra Nova

Petra Nova is a commercially operating CCS facility that was installed at the W.A. Parish coal plant located southwest of Houston in Thompsons, Texas. W.A. Parish has been running since 1977 (GEM 2024), and Petra Nova operated from 2017 to 2019 (DOE NETL 2020) and was restarted in 2023 (Reuters 2023). Petra Nova was intended to remove CO_2 post-combustion from a 240 MW slipstream from Unit 8 (about a third of its total output) of the eight-unit coal plant and would be coupled with EOR. A separate natural gas cogeneration facility was constructed to provide process steam and power for Petra Nova. According to the DOE's technical report on the facility (DOE NETL 2020), Petra Nova had to provide offsets or credits for NO_x to comply with permitted levels (TCEQ 2022) and for VOCs because it was sited in a severe nonattainment zone for ozone. A project report from the Texas Commission on Environmental Quality (TCEQ) indicates that Petra Nova Parish Holdings LLC purchased 2,300 tons of NO_x in the form of credits from NRG (TCEQ 2012), which originally co-owned Petra Nova with JX Nippon—it has since sold its stake to JX Nippon (Buckley 2022). The U.S. Energy Information Administration (EIA) estimated substantial NO_x emissions, not only for the CCS facility (908 to 1,184 tons for the three years it was operational), or over 3,000 tons of NO_x total, but also for the natural gas cogeneration facility, on the order of 467 to 750 tons per year for those years (EIA 2023a). For perspective, the electric cogeneration unit alone, which is something that would not have been needed but for the CCS, accounts for around 10% to 20% of the total NO_x emissions of the entire W.A. Parish coal plant. This figure is jarring given that this eight-unit coal plant is one of the dirtiest polluters and largest sources of NO_x in the state (Shelley 2020).

One of the only existing studies on co-pollutant emissions associated with the carbon capture process is a European Environment Agency (EEA) report from 2011 (EEA 2011). Empirical data that shows the true additive emissions, particularly for NO_x and PM, from operating a pilot or commercial-scale carbon capture facility is scarce. Petra Nova may be the only commercially operating CCS facility in the power generation sector that has openly available SO_2, NO_x, and $PM_{2.5}$ emissions data,[1] and even so, the

[1] Datasets with estimates of NO_x, SO_2, and $PM_{2.5}$ emissions associated with the Petra Nova carbon capture facility: NO_x, SO_2: EIA model estimates (2017, 2018, 2019), row: 'Carbon Capture Plant', column: 'EIA Model Estimates of NO_x Emissions (Tons)' https://www.eia.gov/electricity/data/emissions/
$PM_{2.5}$: eGrid/NEI estimates (2018 and 2019), row: 'W.A. Parish Carbon Capture Plant', column: 'Plant annual $PM_{2.5}$ emissions (tons)' https://www.epa.gov/egrid/egrid-related-materials

accounting is difficult to track. The EIA has historical data on SO_2 and NO_x emissions for Petra Nova showing that it is a contributor to both; however, less clear is the extent to which Petra Nova contributed to additional NO_x emissions on top of that which is associated with the Unit 8 slipstream that would have been emitted with or without the presence of Petra Nova. This dearth of comprehensive or easily traceable emissions data or plant-specific air permits for the few existing plants in operation raises serious questions about the impact of carbon capture facilities on local air quality. At the same time, the imposition of any additional pollution in EJ and overburdened communities that already experience excessive pollution raises an environmental justice concern, and the absence of accessible emissions data only heightens this concern.

Photo: Robert S. Donovan/CC

Threats to health and safety in the transport of CO_2 in pipelines

Reliance on CCS will require an extensive buildout of pipeline infrastructure, as pipelines are the most common way to transport CO_2. CO_2 pipeline construction can contribute to air pollution, cause damage to vegetation and natural habitats, and affect groundwater (S. Chen et al. 2022). Yet again, it is very likely that this will place increased risks in EJ communities that already have disproportionately high levels of risk, as pipeline infrastructure is often sited in areas of greater social vulnerability (Emanuel et al. 2021; Strube, Thiede, and Auch 2021; Weller et al. 2022). Pipelines transporting CO_2 can be particularly hazardous and prone to explosions and leaks. If the CO_2 contains moisture, it can be highly corrosive to pipelines.[10] Between 2003 and 2022, the Pipeline and Hazardous Materials Safety Administration (PHMSA), the agency that oversees CO_2 pipelines, reported a total of 102 incidents, with corrosion being the biggest culprit (Public Sector Consultants 2023). A rupture in a CO_2 pipeline releases large amounts of CO_2. In high concentrations, it can act as an asphyxiant and lead to respiratory complications, altered mental states, and seizures, and increase the risk of death with long exposure (Fogarty and McCally 2010; 2010; Patel and Sharma 2023). In the case of a pipeline rupture, CO_2 will displace oxygen, which can stop vehicles from running and impede evacuation procedures and emergency response (Zegart 2021; PSR and SEHN 2022).

[10] Addressing moisture content in CO_2 necessitates either the use of corrosive-resistant pipeline materials at higher costs or an additional process to dry the CO_2 before it enters the pipeline, adding increased energy requirements and cost (IPCC 2005).

Denbury CO2 Pipeline Explosion in Satartia, MS

A rupture in a CO_2 pipeline operated by Denbury Gulf Coast Pipelines, LLC caused an explosion on February 22, 2020, in the rural town of Satartia, Mississippi, that released 31,405 barrels of liquid CO_2 (DOT 2022). More than 200 people were evacuated and had to shelter overnight at a local middle school, and at least 45 were hospitalized. Local highways were closed (DOT 2022). Residents reported that adults and children lost consciousness, lay on the ground, or were unable to breathe (Simon 2023). Jack Willingham, the emergency director for the county, likened the situation to a "zombie apocalypse" (Simon 2023). Additionally, the displacement of oxygen by CO_2 prevented vehicles from running, which hindered emergency response procedures and forced some evacuees to get out of their cars and walk to safety (Simon 2023). Community members suffered from long-term effects to their respiratory systems and brains, with some needing oxygen tanks for several months after the incident and others experiencing headaches, anxiety, difficulty concentrating, and muscle tremors (Simon 2023). The explosion also impacted livelihoods. For example, one community member had to temporarily stop working at his construction job because of the cognitive issues caused by CO_2 poisoning (Simon 2023).

According to the U.S. Department of Transportation's investigation into the incident, Denbury did not alert emergency responders after the rupture, and, in fact, it was first responders who reached out to the company some forty minutes after the rupture (DOT 2022). This delay "led to confusion in understanding the circumstances associated with the emergency and hindered the ability of first responders and community members to safely navigate the emergency" (DOT 2022, 15). The company was also found to have neglected geohazard risks (e.g., soil instability and land movement) by failing to take any preventive or mitigative measures despite having prior knowledge and experience of these issues (DOT 2022, 15).

Regulatory gaps exacerbate the risks associated with the transport of CO_2. PHMSA has made no real progress on pipeline safety over the past decade; in fact, between 2010 and 2022, there was a slight increase in the number of pipeline incidents deemed "significant" by PHMSA (Caram 2023). Moreover, according to a report prepared for the National Association of Regulatory Utility Commissioners (NARUC) (Public Sector Consultants 2023), challenges exist in determining who is responsible for regulating CO_2 pipelines because the CO_2 can change phase from a supercritical fluid to a liquid while traveling through the pipes. PHMSA currently exercises jurisdiction over pipelines transporting CO_2 as a gas or in a supercritical state, and has only adopted regulations for when there is a concentration of 90% or more of CO_2 compressed into a supercritical state (Lockman 2023).

Geohazards are the leading cause of high-profile pipeline failures, such as the 2020 pipeline incident in Satartia, Mississippi, described in the breakout box; however, PHMSA does not have detailed standards to assess or address them (BoldNebraska 2023). This deficiency is particularly concerning for EJ communities, where there may be less infrastructure to deal with disasters and emergency response and recovery (Jerolleman and Waugh 2022). Following the pipeline explosion in Satartia, PHMSA introduced new safety rulemaking to update standards for CO_2 pipelines (PHMSA 2022). However, PHMSA is not expected to issue a Notice of Proposed Rulemaking (NOPR) until June 2024, and there is no set date for rule finalization (CRS 2023). There are also exceptions to federal regulations that allow states or counties to have pipeline routing authority, as well as the ability to regulate nuisance, pollution, and hazard mitigation during and after construction, the depth to which CO_2 pipelines are buried in agricultural land, emergency response, and abandoned CO_2 pipelines. State-by-state or county-by-county authority over these important aspects of CO_2 pipeline regulation signifies the potential for huge regulatory gaps, mismanagement, or at least lack of accountability and transparency, and it could impact EJ communities that reside in areas with limited capacity to oversee these pipelines. While PHMSA undertakes rulemaking on CO_2 pipelines, numerous public health, EJ, and environmental experts have asked the agency to advise states to establish a moratorium on CO_2 pipelines in light of the risks, knowledge gaps, and regulatory deficiencies (FWW 2023). This request has not been acted upon to date.

The magnitude of new pipeline buildout will exacerbate the threats described above. Existing oil and gas pipelines are not well suited for transporting CO_2, as they are designed for lower pressures, and repurposing

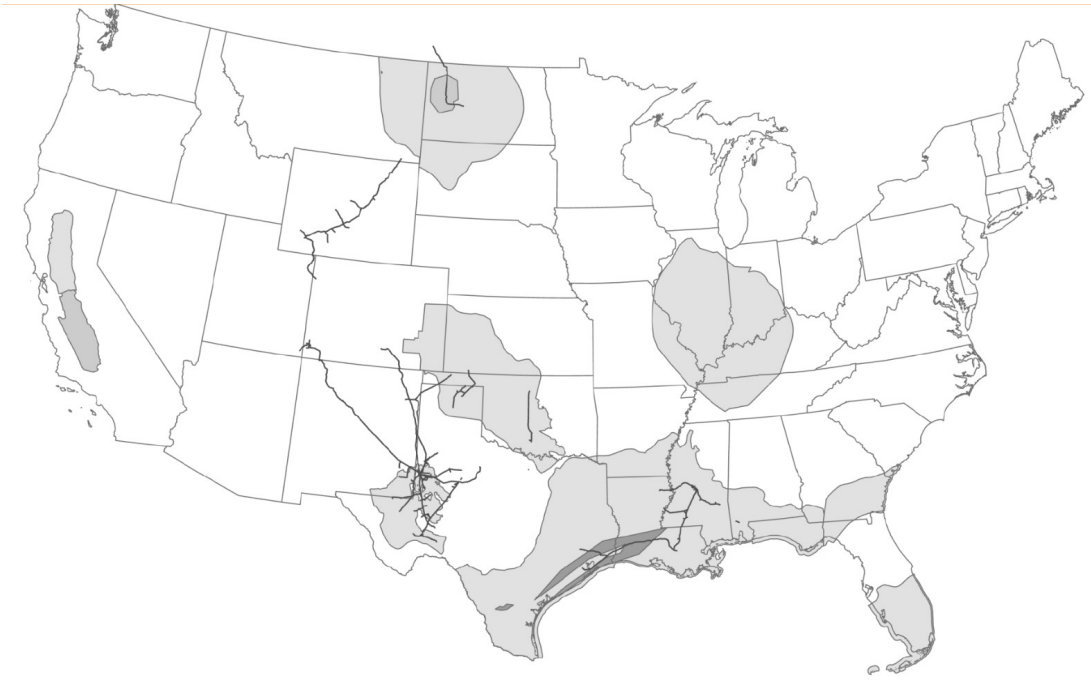
existing pipelines can be costly or impractical (Blackburn 2022; NPC 2019). Projections show that CO_2 pipeline infrastructure may expand from around 5,150 miles today to between 30,000 to 96,000 miles by 2050 based on various scenarios (see Figure 3)[11] (Fahs et al. 2023). While this report does not present an explicit spatial analysis for CO_2 pipeline expansion, due to the location of power plants in EJ communities, as described earlier, it is all too likely that the buildout of pipelines will impact these areas throughout the United States and add further strain to already overburdened communities. The EJ implications of pipeline buildout will likely include impacts to Indigenous communities and sovereignty if the buildout continues the historic pattern of industry-led pipeline development on Indigenous lands in the United States (Strube, Thiede, and Auch 2021). As evidenced by the examples of the Dakota Access and Keystone XL pipelines, among others, potential effects could include devastating damage to Indigenous communities' environment, health, and sites of significant cultural importance (Emanuel et al. 2021).

Lastly, the risks posed by pipelines are inadequately addressed, not only because of PHMSA's failure to ensure safe CO_2 transport, but also because of the lack of uniform siting authority for pipelines, since this responsibility is split between multiple federal agencies (e.g., the EPA and U.S. Army Corps of Engineers) and individual states. Lack of uniformity makes it difficult for communities to communicate their concerns or have them adequately addressed (Public Sector Consultants 2023).

Additional hazards during CO_2 storage

When CO_2 is injected and stored in underground geologic formations, such as saline aquifers, unmined coal beds, and depleted gas or oil reservoirs, leakage can contaminate groundwater sources. CO_2 leakage can decrease the pH of the groundwater and cause a release of toxic metals from the aquifer, which can contribute to carcinogenic and noncarcinogenic health effects (Siirila et al. 2012). Our review of the evidence did not yield any data on the co-location of geologic storage sites in EJ communities, likely because commercial-scale storage projects are still at a nascent stage; however, we did find significant overall uncertainty around the speed, location, and storage

[11] Image sources: Reproduced from Larson et al. 2021. Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton, NJ: Princeton University. https://www.dropbox.com/s/ptp92f65lgds5n2/Princeton%20NZA%20FINAL%20REPORT%20%2829Oct2021%29.pdf?dl=0 and Great Plains Institute (GPI). 2020. Transport Infrastructure for Carbon Capture and Storage: Whitepaper on Regional Infrastructure for Midcentury Decarbonization. Minneapolis, MN: GPI. https://www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf



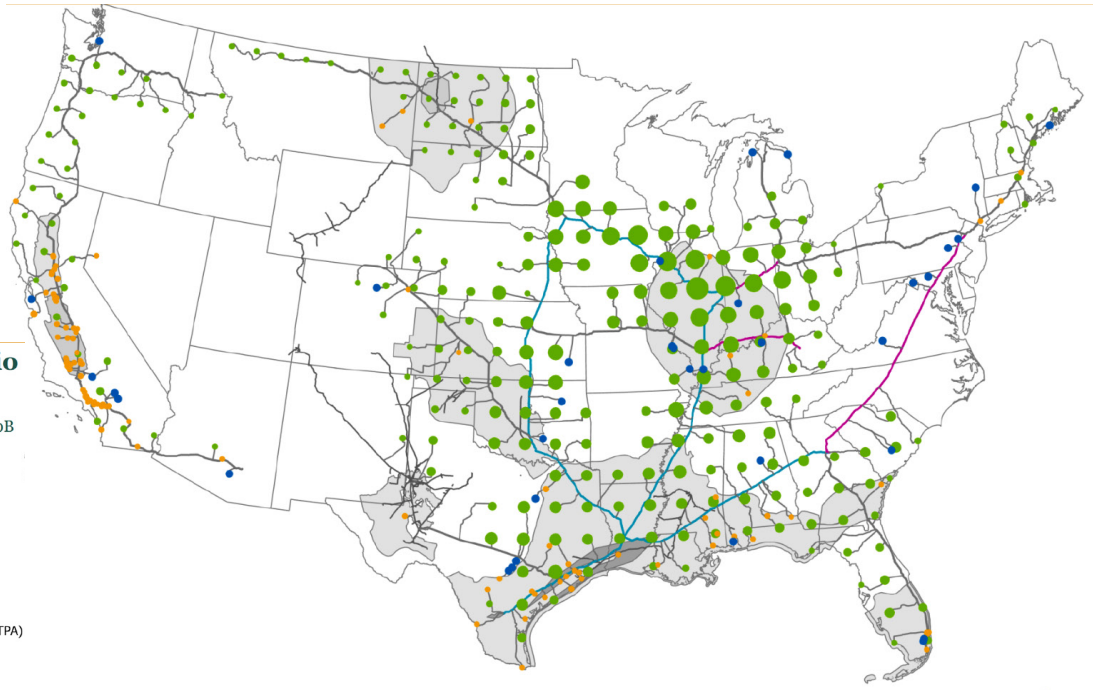
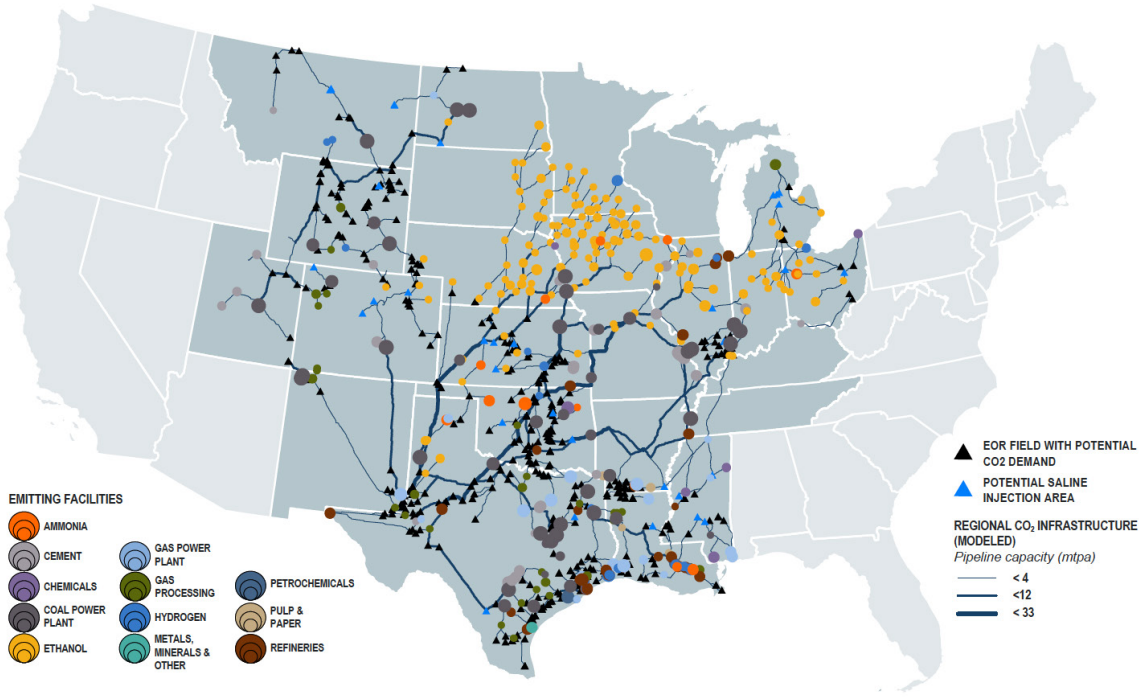


Figure 3.

Possible expansion of CO_2 pipeline network according to various scenarios. Image 1: Net-Zero Americas, 2020, 4,500 miles (black lines are CO_2 pipelines, gray areas are CO_2 storage basins); Image 2: Net-Zero Americas, 2050 scenario, 70,000 miles; Image 3: Great Plains Institute, 2050 scenario, 30,000 miles.



potential of geologic CO_2 sequestration (Lane et al. 2021; S. Chen et al. 2022; Gholami, Raza, and Iglauer 2021). The same is true of offshore geologic storage, where leakage has been detected even in sites that were considered well characterized (Hauber 2023; Williamson 2023). (For more details on challenges with storage, see Section IV(B)).

Similar to the issue of transport, the current regulatory landscape fails to adequately address the risks that communities near storage areas can face. CO_2 storage is currently regulated under the Safe Drinking Water Act (SDWA), which created a provision for Underground Injection Control (UIC), a program now run by the EPA. The UIC is intended to protect underground sources of potable water. In 2008, the EPA proposed a new class of injection wells (Class VI) to regulate for risks specifically related to geologic CO_2 injection and storage, including its corrosive properties, presence of impurities, buoyancy, and mobility within geologic formations (EPA 2008; Jones 2022). As of 2022, two states, Wyoming and North Dakota, had primacy over Class VI well permitting, but several others were undergoing the application process (Zapantis et al. 2022). The EPA has the authority to grant primacy to states, which then become the primary authority to regulate and permit injection wells (EPA 2022). In January 2024, Louisiana became the third state to obtain primacy (EPA 2024a). The EPA made the decision to grant Louisiana primacy over the objections of environmental and EJ organizations that were concerned about the state's poor track record of environmental protection

and regulatory capture by fossil fuel interests in many of these states (see, for example, report series on regulatory capture in Texas (Texans for Public Justice and Commission Shift 2021)) generally, and its existing problems with orphan and leaking wells specifically (Earthjustice, n.d.; NAACP 2023; DSCEJ 2023). For example, Louisiana has nearly 4,500 abandoned or orphaned oil and gas wells (LA DNR, n.d.), with likely many more unaccounted for (Earthjustice, n.d.). As of January 2024, several other states, including Texas, West Virginia, Arizona, and Pennsylvania have either started or announced their intention to start applications for primacy (MRCI 2023).

An additional concern is the fact that well operators may not go through the Class VI permitting process at all. Many states already have primacy over Class II oil and gas well permitting, and Class VI rules allow Class II wells to be used for long-term CO_2 storage. Class II regulations are even less protective than Class VI regulations (Mordick and Peridas 2017), and a Class II well can be used for long-term CO_2 storage without the need to acquire a Class VI permit if the primary purpose of the well is something other than long-term CO_2 storage, or if there are no increased risks to underground sources of drinking water (Powell 2023).[12] Concerningly, it is the well owner or operator who is tasked with assessing whether a Class VI permit is needed, and there is no requirement to notify regulators of the determination (Powell 2023). With this system, it is eminently likely that the application of Class VI rules to CO_2 storage in Class II wells will be extremely inconsistent and will not happen until after harm to communities and the environment has occurred (Powell 2023). Further, even if the well owner or operator decides that Class VI rules apply to a Class II well, full compliance is not required of Class II wells, which are used largely for enhanced oil or gas recovery and have different engineering and construction from Class VI wells (Powell 2023).

Research has uncovered significant and troubling disparities regarding implementation and enforcement of the SDWA. A regression analysis of 1,693 community water systems in California from 2000 to 2018 found that EJ communities were disproportionately exposed to higher rates of health-based drinking water violations (Allaire and Acquah 2022). A nationwide, county-level analysis of EPA data from 2016 to 2019 found that there were disparities in violations, as well as enforcement, of the SDWA (Fedinick et al. 2019). Of

[12] Class II wells are largely used for enhanced oil or gas recovery, and as noted earlier, the primary destination for captured CO_2 is EOR. Section IV.A will address the climate mitigation implications of this fact (Powell 2023). Class VI wells are used for geologic storage of injected CO_2; a more detailed description of the differences between the two types of wells is provided elsewhere (Jones 2020).

the sociodemographic characteristics analyzed, race, ethnicity, and language spoken were the set of characteristics most strongly associated with slow and inadequate enforcement of the SDWA. Another national analysis using American Community Survey and EPA data found that, nationally, community water systems in violation of the SDWA were correlated with higher rates of poverty (Mueller and Gasteyer 2021). These outstanding problems point to continued impacts and disparities to the detriment of EJ communities as CO_2 storage develops.

B. Hydrogen co-firing

Harmful emissions from hydrogen production

The co-firing of hydrogen-blended fuel at power plants requires hydrogen to be produced, and currently hydrogen is mostly produced from fossil fuels, as noted in Section II.B. Whether the production of fossil fuel-based hydrogen is paired with carbon capture, (in which case all of the concerns with carbon capture described in the preceding section apply) or undertaken without carbon capture, the reliance on a fossil fuel feedstock like natural gas or coal raises myriad concerns. There are numerous health and environmental impacts associated with fossil fuel extraction, production, transport, and storage, including air pollution from pollutants like VOCs, PM, and NO_x; water contamination; loss of ecosystem services; linkages between proximity to extraction sites and higher mortality rates, cancer risk, respiratory issues, and preterm births; safety risks from processing and manufacturing; and leakage, spills, and explosions during transport (Donaghy et al. 2023). When a fossil fuel like shale gas—a typical feeder stock—is used for hydrogen production, it is necessary to use techniques such as hydraulic fracturing (fracking) in its extraction, which results in more fracked gas wells in areas already burdened by heavy extractive industry (EHP 2022). Studies have highlighted the negative health effects associated with fracking, including respiratory health issues and adverse birth outcomes (Black et al. 2021). A nationwide assessment of exposure to flaring from directional drilling and high-volume fracking reported that Black, Indigenous, and People of Color were disproportionately exposed to flaring at well sites, which impacts air and water quality, disrupts social fabrics, increases noise and traffic, and impacts fetal growth and preterm birth (Cushing et al. 2021). In further evidence of inequitable oil and gas infrastructure siting, one study found that both active and inactive wells are disproportionately sited in redlined neighborhoods in the United States (Gonzalez et al. 2023).

While more attention has been paid to the GHGs emitted from SMR, the SMR process to produce hydrogen also emits harmful co-pollutants, including VOCs, SO_2, CO, NO_x, $PM_{2.5}$, PM_{10}, ammonia, and lead (P. Sun et al. 2019; Cho, Strezov, and Evans 2022). Emissions from the SMR process can come from auxiliary combustion sources like heaters, boilers, and engines. Other sources include emissions from flaring, fugitive emissions, and hydrogen plant process emissions (P. Sun et al. 2019). Most hydrogen production occurs near oil refineries, which increases co-pollutant emissions and risks to communities living near these already-polluting sites (Saadat and Gersen 2021). Risks are particularly heightened for Communities of Color, which are disproportionately exposed to toxic burdens from oil refineries (Donaghy et al. 2023) and face higher cancer risk from exposure to these facilities (Fleischman and Franklin 2017). Adding hydrogen production facilities to areas that are already overburdened with other fossil fuel infrastructure will likely compound existing disproportionate impacts on EJ communities.

Methane leakage in hydrogen production, transport, storage, and use

During the hydrogen production process, there will be methane and hydrogen leaks both upstream and downstream (Ocko and Hamburg 2022). These leaks can occur anywhere from the point of extraction, through transportation in pipelines, to the final destination of the hydrogen (Burns and Grubert 2021; Lockman 2023) (Burns and Grubert 2021; CGEP 2022). With these concerns in mind, scientists have conducted compelling research on the GHG footprint of blue hydrogen that considers methane leaks, for which some studies fail to account (see, e.g., Osman et al. 2022). The leakage of methane undermines the climate mitigation intent of deploying blue hydrogen, as discussed in greater detail in Section IV. Methane is a GHG that also causes harmful localized health impacts through the formation of particulate pollution and ground-level ozone, which aggravate respiratory issues and contribute to cardiovascular morbidity and mortality, among other challenges (EDF, n.d.; Sarofim, Waldhoff, and Anenberg 2017). The impacts from methane leakage along the hydrogen supply chain will add to the disproportionate burden that EJ communities already face from existing oil and gas extraction, pipeline, and power plant infrastructure.

Pipeline explosions and leaks in the transportation of hydrogen

There are also risks and dangers associated with transporting hydrogen via pipeline as currently envisioned. Many of these risks stem from hydrogen's

physical properties—low autoignition temperature,[13] high combustion efficiency, wide flammability range,[14] and small molecule/atom size leading to greater potential for leakage and greater dispersion once released. Employing natural gas pipelines that were not designed specifically for hydrogen or hydrogen blends makes transport even more dangerous (Clarkson 2023; Kuprewicz 2022b). According to the Pipeline Safety Trust, materials such as steel and polyethylene are not suitable for transporting hydrogen because of the potential for embrittlement, cracking, and other damage. Operators would need to upgrade entire existing pipeline systems to minimize the potential for pipeline failure (Clarkson 2023). Currently, there are only around 1,500 miles of pipelines in the United States specifically designed for hydrogen production, and there is a lack of regulation for its specific transportation by PHMSA, the government agency responsible (Kuprewicz 2022b).

Existing evidence suggests that EJ communities will likely bear the risk of pipeline explosions and leaks (Emanuel et al. 2021; Strube, Thiede, and Auch 2021; Weller et al. 2022). For example, researchers have found that areas of greater social vulnerability face higher pipeline densities (Emanuel et al. 2021). Additionally, an analysis of natural gas leaks in local distribution systems of 13 U.S. metropolitan areas found that leak densities increased with higher proportions of People of Color and decreasing median household income (Weller et al. 2022). Thus, whether hydrogen is transported via new pipelines or repurposed existing pipelines, it is likely that the risks associated with transporting hydrogen and hydrogen blends will fall on EJ communities.

NO_x emissions from hydrogen combustion

For use in the power sector, hydrogen-blended natural gas would be combusted as a supposedly lower-carbon fuel. However, this application poses a threat to public health, as the combustion of hydrogen or hydrogen-blended natural gas, in the presence of air and at high temperatures, leads to NO_x emissions, and by extension the formation of ozone and PM (Lewis 2021). Notably, hydrogen co-firing can yield more NO_x emissions than burning natural gas alone (McNamara 2020). A study by Cellek and Pinarbasi (Cellek and Pınarbaşı 2018) found that hydrogen co-firing can produce up to six times more NO_x emissions than combusting methane on its own. Other estimates have varied; however, the general conclusion is that NO_x emissions do

[13] This is the lowest temperature required to ignite a gas or vapor in air spontaneously, without a flame or spark.
[14] This is the range of concentrations at which the substance will ignite or combust when mixed with air.

increase, primarily due to the fuel's higher combustion temperature (Pan et al. 2023). The DOE acknowledges in its 2020 Hydrogen Program Plan that more research is needed to address the control of NO_x emissions from hydrogen co-firing (DOE 2020a). It states that emissions from co-firing low-hydrogen blends might be controlled, but for blends with high levels of hydrogen it is difficult to control emissions, and technologies that attempt to do so are not yet proven (DOE 2020a, 24–25; Ramanan, Milford, and Mullendore 2020). Existing NO_x emission controls are not formulated for blends above 30% hydrogen (Ramanan, Milford, and Mullendore 2020), despite intentions to employ higher percentage hydrogen blends (see, e.g., EPA 2023). If located in or near EJ areas, hydrogen co-firing can add more GHG co-pollutants to these communities, which already face disproportionate exposure to co-pollutants (Lelieveld et al. 2015; T. Chen et al. 2007; Nitschke 1999; Guo et al. 2004; CDC 2021; Sundblad et al. 2004).

NO_x exposure over short periods and long term is known to cause respiratory issues (EPA 2016c), and PM and ozone have been associated with a host of health impacts, including premature mortality, respiratory symptoms, cardiovascular events, and adverse birth outcomes (EPA 2015; 2016b). When NO_x reacts with other chemicals in the air, this reaction can also lead to the precipitation of acid rain and to nutrient pollution in coastal waters (EPA 2016c). All of these pollution impacts will be added to the existing burdens already faced by communities living near power plants, exacerbating environmental injustice (Boyce and Pastor 2013; Tessum et al., 2021; Morello-Frosch 2011; Lam et al. 2022).

IV. Inefficient and Ineffective Climate Mitigation

The previous section describes how carbon capture and hydrogen co-firing in the power sector pose serious threats to the environment and public health, particularly for already overburdened environmental justice communities in close proximity to related infrastructures. These arguments alone would be enough to warrant rethinking their deployment, even if

doing so were proven to be an effective climate mitigation strategy. Evidence suggests, however, that there are questions about the efficacy of CCS and hydrogen co-firing in this regard, particularly for the power sector. Although concerns about deploying these technologies in any application raise the same or similar questions in terms of risks to EJ communities, their climate mitigation potential is even less supported in the power sector, which already has the known and proven solution of decarbonization through renewables. This section briefly outlines some of the evidence on why these strategies may be inefficient or ineffective from a mitigation standpoint and calls into question the argument of climate benefits as a justification for placing additional risks on already overburdened communities. The potential for carbon management approaches to enable carbon lock-in and perpetuation of fossil fuels in the power sector, thereby delaying the transition to renewable energy, is itself an environmental justice concern, as EJ communities are among those that have been and will continue to be hit hardest by the climate impacts that will ensue if we fail to implement climate mitigation grounded in proven renewable energy, regenerative, and just transition approaches (Morello-Frosch Rachel and Obasogie 2023).

A. Fossil fuel industry influence and carbon lock-in

Multiple researchers have noted that investing in CCS and hydrogen can enable carbon lock-in, which would prolong the United States' dependence on polluting fossil fuel infrastructure (Swennenhuis, de Gooyert, and de Coninck 2022; McLaren 2012; Szabo 2021). The fossil fuel industry has played a role in the proliferation of these technologies as part of a national energy transition agenda (Kusnetz 2021; Si et al. 2023; Halper 2022; Earthjustice 2023) despite their many shortcomings in addressing equity concerns and reducing emissions, as outlined in this paper. Experts have expressed concern that carbon lock-in not only siphons funds for risky carbon management technologies but also delays the transition to affordable and proven renewable alternatives in the power sector that can reduce both co-pollutant emissions and GHGs (Butler 2020; Robertson and Mousavian 2022; Denholm et al. 2022). A recent study that modeled projected U.S. power sector emissions under several scenarios and factored in the 45Q tax credit demonstrated that, with high capture rate assumptions, even though plants are applying CCS, their overall emissions range from only minorly decreasing to actually increasing quite substantially because of the added capacity factor and lifespan extension of the plants (Grubert and Sawyer 2023). We will discuss these

topics in greater detail in our forthcoming policy paper.

A prime illustration of how CCS fails to deliver on climate mitigation is the fact that the predominant use of captured carbon today is enhanced oil recovery (EOR) (Zapantis et al. 2022; CBO 2023), which is antithetical to a transition away from fossil fuels. The process of EOR is used to extract more oil from existing wells that is then transported and combusted, thereby generating emissions, while the EOR process itself also produces emissions (Millemann et al. 1981). Thus, when CO_2 captured from CCS is used for EOR, the entire process is unequivocally net additive to CO_2 emissions and therefore fails as a climate mitigation strategy (Sekera and Lichtenberger 2020). Additionally, while in theory some CO_2 could be retained underground in existing wells, these wells are at risk of CO_2 explosions, or "blowouts" (Mordick and Peridas 2017).

Even though the risks of CCS and hydrogen are known, CCS has been contested for decades (e.g., Roberts 2007; Tyree and Greenleaf 2009), and billions of dollars in past direct government investments and subsidies have failed to bring it to scale (Stephens 2014), the public sector has continued to make outsized investments in these technologies via increased funding and tax credits. A cursory look into the fossil fuel industry's other recent activities in addition to EOR indicates their alignment with a carbon lock-in trajectory. In fact, recent reports observe that the industry is regressing on its climate policies, abandoning its emissions reductions and renewable energy targets, and in some cases maintaining or even increasing oil and gas production (Yoder 2023; Bousso 2023). At the same time, companies like Chevron, Occidental, ConocoPhillips, and ExxonMobil are rushing to lease nearly 1.5 million acres of land for onshore and offshore carbon storage in Texas, Louisiana, and the Gulf of Mexico (Dvorak 2023), signaling their intent to capitalize on federal support for carbon management.

B. Uncertain and slow to scale carbon storage sites

Even when the CO_2 captured is not used for EOR, a further challenge for CCS as a climate mitigation strategy lies in the uncertainty about the location and sequestration permanence of geologic CCS storage sites. As described in Sections II.A and III.A.3, geologic sequestration refers to storing CO_2 in underground geologic formations (Kelemen et al. 2019).

Leakage during storage can take place, causing CO_2 to escape into the atmosphere and harming surrounding plants and wildlife (S. Chen et al. 2022). A DOE NETL report that classified different failure modes of CO_2 storage

concluded that CO_2 storage "can be conducted safely, resulting in minimal environmental impact and reduced likelihood of failure modes occurring if storage sites are properly selected, characterized, operated, monitored, and closed [emphasis added]" (Warner et al. 2020, 11). However, past projects have shown that even a rigorous geologic assessment may not be enough to mitigate leakage problems. In the case of two offshore CCS storage projects in Norway, CO_2 migrated from the original storage site in one project, and in the other, storage lifetime decreased from eighteen to two years once the project started operations, resulting in additional costs for emergency remediation and long-term alternatives (Williamson 2023; Hauber 2023). These two projects are located within two of the most characterized geological fields in the world, and even then it was difficult to predict their security and stability, thus presenting concerns for the long-term financial and technical viability of carbon storage (Williamson 2023; Hauber 2023).

Researchers have estimated that a CO_2 leakage rate of 1% per year or higher would mean that CCS could not be considered a meaningful climate change mitigation avenue (van der Zwaan and Smekens 2009). Overall, in practice, CO_2 from CCS is not all permanently stored. CO_2 used in EOR is a net additive to GHGs and can result in well blowouts, as well as chronically or acutely leak during transport, as was the case in Sataria, and CO_2 storage raises questions about both the potential for leakage and the longevity of storage. The systems in place for tracking the life cycle of CO_2 have revealed inconsistencies. In one example, an analysis by NRDC and Greenpeace submitted to the Internal Revenue Service reported that operators of facilities injecting CO_2 for long-term storage were not complying with monitoring and reporting requirements, and that they claimed 62.7 million metric tons of CO_2 for tax credits, about ten times more than what the EPA had documented (6 million) (Mordick and Noël 2019).

Although some geological storage is planned for the power sector, there is still significant uncertainty around the deployment speed, location, and potential of geologic storage, as well as a lack of public discourse about these unknowns (Lane et al. 2021; S. Chen et al. 2022). Maps of where geologic sites might be located are extremely vague (see, e.g., DOE NETL, n.d.-a; Fahs et al. 2023). Limited advances in deploying commercial-scale storage continue to be one of the biggest challenges to CCS, both on a domestic scale and a global scale (Damiani 2022; Zapantis et al. 2022; Yuting Zhang, Jackson, and Krevor 2022; IEA 2022). In order for CCS to effectively serve as a climate mitigation strategy and reduce CO_2 emissions, captured CO_2 must be permanently stored. However, feasible geologic storage locations that account for their

declining capacity to store additional CO_2 over time are not well characterized (Lane et al. 2021), and there is uncertainty about the long-term implications of storing CO_2 in the ground (Alcalde et al. 2018; Gholami, Raza, and Iglauer 2021; Koornneef et al. 2012). Furthermore, both onshore and offshore CO_2 storage have been linked to detrimental environmental impacts. For example, CO_2 buildup during onshore storage can cause a leakage of brine that contaminates shallow groundwater resources and may necessitate removal (Cihan, Birkholzer, and Zhou 2013; Kelemen et al. 2019; Meehan et al. 2023), and could also activate a fault (Oruganti and Bryant 2009; Warner et al. 2020; National Research Council 2013). Additionally, the hazard-prone area may be much larger than the region where the CO_2 has been injected (its plume) (Oruganti and Bryant 2009). CO_2 leakage from abandoned or orphaned wells used for storage must also be considered (Ide, Friedmann, and Herzog 2006).

Offshore CCS storage has been proposed as an alternative storage option (DOE NETL, n.d.-b), but it can contribute to ocean acidification (IPCC 2005), which can negatively impact marine life and ecosystems (Wannicke et al. 2018). No regulations currently exist to guard against these environmental effects. In another example of regulatory deficiency, an investigation of monitoring, reporting, and verification plans found that they often lacked detail, were not required to follow any specific strategies or use specific tools, and presented insufficient enforcement mechanisms (Bains 2023). As of February 2024, there still appears to be no established permitting process for offshore storage, presenting additional concerns for future offshore storage projects (see, e.g., Huang 2023).

C. CCS's energy penalty and capture rate assumptions

In addition to the challenge of CO_2 storage, another issue that undermines CCS's efficiency as a climate mitigation strategy is the amount of energy needed to power the carbon capture process, sometimes referred to as the CCS energy penalty. CCS requires additional energy to power the CO_2 separation and compression processes (EEA 2011; Aghel et al. 2022). Given that the majority of the U.S. electric grid relies on nonrenewable sources (EIA 2023b), it is more than likely that this energy will be derived from fossil fuels and therefore contribute to additional health-harming co-pollutants at the point of fuel extraction and combustion, as discussed in Section III, as well as to GHGs that undermine the mitigation intent.

While some studies have estimated the energy penalty for different fuel types and capture processes (e.g., Vasudevan et al. 2016; Romeo, Lisbona, and Lara 2019), most assessments are based on simulations or small-scale experimental testing, not in situ testing of operating CCS facilities. A review by Wang et al. (Y. Wang et al. 2022) found that studies have reported energy penalties of between 15% and 44% for CCS generally (not specific to the power sector). Additionally, the embodied emissions of new CO_2 pipeline buildout, pipeline leakage, and underground storage leakage can all contribute to increased CO_2 emissions along the CCS life cycle.

CCS projects for direct application in the power sector and for the production of blue hydrogen have also assumed a high rate of CO_2 capture to justify the use of this strategy as a climate mitigation approach (Longden et al. 2022). A prime example of this is the commercial-scale CCS facility Petra Nova (DOE NETL 2020), which was introduced in the breakout box in Section III.A.3. Referring to an analysis by the Institute for Energy Economics and Financial Analysis (IEEFA) that factored in the emissions of the gas-fired combustion turbine used to power Petra Nova (Mattei and Schlissel 2022), the WHEJAC has made the following observation: "The projected high capture rates for CCS have not been produced or verified. Predicted levels were 90 percent but estimates of real capture rates are at about 55-58 percent and further monitoring data is needed to verify Petra Nova's claim of a 90 percent capture rate" (WHEJAC 2023, 18). Moreover, this capture rate does not account for upstream coal mining emissions of methane or the downstream emissions from the use of captured CO_2 for EOR (WHEJAC 2023, 18). Another IEEFA report on blue hydrogen documented lower than predicted CO_2 capture rates for the only three commercially operating blue hydrogen projects globally, all produced using SMR (Schlissel and Juhn 2023, 18).

D. Blue hydrogen's GHG footprint

Researchers have raised serious questions around the "low-emission" label of blue hydrogen, as studies have shown it to have a relatively large GHG footprint (Longden et al. 2022; Howarth and Jacobson 2021). When hydrogen is separated from coal or natural gas, significant CO_2 and fugitive emissions, including methane leaks, occur along the process, from feedstock extraction to venting, flaring, and transportation (Mac Dowell et al. 2021; Cho, Strezov, and Evans 2022). Fugitive emissions are often neglected in calculations estimating the GHG reduction potential of hydrogen (Longden et al. 2022), despite the fact that methane is an even more potent heat-trapping GHG

than CO_2 (EPA 2016a). In fact, studies have shown that methane accounts for approximately 30% of global warming since the industrial revolution (IEA 2022). Recent research on methane leakage from blue hydrogen demonstrates this life cycle problem. One study estimated that the emissions intensity of blue hydrogen, or hydrogen produced through SMR or gasification and coupled with CCS, would be higher than that of natural gas, assuming a carbon capture rate of 56% and a fugitive emissions rate of 3.5% (Longden et al. 2022). Even at a "best case" capture rate, blue hydrogen would only have a 17% lower emissions intensity (measured in kg CO_2e/GJ) than burning natural gas directly without CCS (Longden et al. 2022). Howarth and Jacobson (2021) found that across a range of fugitive emissions rates (as low as 1.5%) and carbon capture rates (as high as 90%), blue hydrogen's GHG footprint is still as large as or larger than that of natural gas.

Lastly, while some of the CO_2 is released in a concentrated stream that facilitates capture, additional emissions come from a dilute stream of flue gases that are released when the feedstock is burned to power the SMR process. Capturing these flue gas exhaust emissions is expensive and difficult (Longden et al. 2022).

In addition to the methane leakage, all the issues associated with CCS that have been highlighted in this report, such as the energy penalty, are applicable to blue hydrogen as well.

Green Hydrogen

While hydrogen derived from fossil fuels accounts for the vast majority of hydrogen produced today (as noted above), there has been increasing attention on producing hydrogen through electrolysis. According to the scientific literature, the production of hydrogen via electrolysis requires substantial water and energy inputs. The evidence from calculating the water footprint of hydrogen produced using electrolysis in situ is higher (Shi, Liao, and Li 2020) than theoretical values relied on by the EPA (EPA 2023, 33315) and others (Beswick, Oliveira, and Yan 2021). One group of researchers points to the rate being typically 25 percent higher than the theoretical conversion rate of 9 kg of purified water consumed per kg of hydrogen produced (Shi, Liao, and Li 2020). Another group observes that the rate can range from 10 kg to as much as 22.4 kg of water per kg of hydrogen based on varying electrolyzer performances and manufacturer specifications (Simoes et al. 2021). More important, theoretical figures account only for water used directly in the electrolysis phase, whereas the indirect water consumption added by the energy and equipment used for electrolysis can drastically increase the rate (Shi, Liao, and Li 2020; Mehmeti et al. 2018).

High water use is also needed for other chemical processes in hydrogen production, such as cooling, post-treatment, and even desalination if seawater is used (DiFelice 2023). One estimate found that of the 50 MMT of hydrogen that the DOE proposes to produce in the United States over the next 25 years, up to 1 trillion gallons of fresh water or 4.6 trillion gallons of seawater would be required to produce the hydrogen (DiFelice 2023). This additional water usage can increase the strain on water resources, especially in drought-stricken areas. Even when they yield a wide range of estimates, life cycle analyses point toward the same general conclusion: Theoretical figures (Beswick, Oliveira, and Yan 2021; EPA 2023) can underestimate the footprint by at least an order of magnitude. There are also significant water consumption and water scarcity issues even with hydrogen produced using electrolysis powered by wind or solar (Mehmeti et al. 2018; Shi, Liao, and Li 2020). Water scarcity is an important factor to consider in terms of the climate mitigation potential of green hydrogen, as climate change may exacerbate areas experiencing drought.

Aside from the water footprint, the production of hydrogen by electrolysis requires substantial energy inputs. While many proponents of green hydrogen, including the EPA, state that the energy should be drawn from low-GHG sources like wind and solar energy (EPA 2023, 33310), diverting renewable energy for hydrogen production rather than sending it directly to

the grid means efficiency losses from converting renewables to electricity and then using that electricity to produce hydrogen (Walsh and DiFelice 2022; Ueckerdt et al. 2021; Nature 2022).[1] Some groups have argued for a set of criteria known as the "three pillars," additionality, regional deliverability, and time-matching, to try to ensure that meeting the energy needs for electrolysis does not lead directly or indirectly to increased fossil fuels on the grid (McNamara 2024). However, even if these criteria were applied ubiquitously, it still does not mitigate concerns around environmental justice, water scarcity, high cost, and the inefficiencies of using renewable energy to produce a fuel to serve as another power source. Electrolytic hydrogen production has an energy requirement of around 50 to 60 kWh/kg H_2, and this large energy expenditure is the main reason for the high cost of electrolysis (Ivy 2004; Buttler and Spliethoff 2018; Singh Aulakh, Boulama, and Pharoah 2021; IRENA 2020). Despite decades of investigation into electrolysis for its application in hydrogen production, it still represents a small fraction (estimates range from less than 0.1% to 2%) of total hydrogen production due to its high costs (IEA 2019; F. Sun et al. 2021).

Photo credit: NASA Kennedy/CC

[1] Bear in mind that the proposed BSER entails using the hydrogen in hydrogen mixing and combustion, engendering the co-pollutant impacts described in Part I. The critique here focuses on the wasted energy.

E. High costs and underperformance of CCS & hydrogen

Despite significant government investments in CCS and hydrogen projects, the track record of existing projects reveals that carbon capture at power plants has failed to work at scale. The significant public investment in CCS and hydrogen as a climate mitigation strategy represents opportunity costs for investing in a complete transition to renewable energy sources. These sunk costs can extend the lifespan of existing fossil-based power infrastructure and divert precious resources from EJ communities seeking to benefit from a just energy transition. Thus, high costs coupled with underperformance of these approaches as climate mitigation strategies can render these investments detrimental to both climate and EJ goals. As described in the earlier subsections of Section IV, some ways in which CCS and blue hydrogen underperform include the associated energy penalty, capture rates that are higher in theory than in practice, uncertainties around CO_2 storage deployment and storage permanence, and methane leakage from blue hydrogen production.

The DOE Fossil Energy and Carbon Management Research, Development, and Deployment program has funded CCS R&D since at least 1997 (Jones and Lawson 2022). Between 2010 and 2017, the DOE spent $1.1 billion on nine CCS demonstration projects (GAO 2022). Despite evidence against using public funds to subsidize commercial deployment of CCS (Sekera and Lichtenberger 2020) and the widespread failure of CCS demonstration and commercial-scale projects (GAO 2021; Robertson and Mousavian 2022; Swartz 2021), the 2021 Infrastructure Investment and Jobs Act (IIJA) allocated $8.5 billion (nominal dollars) in funding for CCS from 2022 to 2026, a subset ($2.6 billion) of which is for six demonstration projects, and the IRA increased tax credits for CCS and hydrogen (Jones and Lawson 2022; GAO 2022). Estimates for the total amount of credits vastly differ depending on the model used, with those for the total amount of credits through 2031 ranging from $3.2 billion to $100 billion (Bistline, Mehrotra, and Wolfram 2023). Carbon capture from a natural gas power plant can cost between $49 and $150 per ton of carbon captured, and $20 to $132 per ton for coal plants, making them uneconomical even with increased tax credits (Moch, Xue, and Holdren 2022). Subsequent analyses that factor in Inflation Reduction Act (IRA) tax credits continue to find that CCS is unnecessary and too expensive as an option for decarbonizing the power sector (Clemmer et al. 2023).

The IIJA also allocated $8 billion to the development of hydrogen

production projects, one of which will be dedicated to blue hydrogen production (Mattei 2022), and the IRA's 45V tax credits "offer huge, uncapped incentives for 'clean' hydrogen that could run up to more than $100bn" (Budden and Fakhry 2023). However, the cost of producing blue hydrogen, which is driven by the price of capital expenditures and the cost of the feedstock, is extremely uneconomical, especially when high capture rates are desired (Schlissel et al. 2022; Longden et al. 2022). Adding CCS to hydrogen production from fossil fuels increases the unit cost from an estimated $1.66 to $1.84 per kg without CCS (gray hydrogen) to $2.09 to $2.23 per kg with CCS (blue hydrogen) (Longden et al. 2022). Subsidies have been necessary to make blue hydrogen production possible. For example, two-thirds of the cost, or $284 million of $431 million, to build the single commercial blue hydrogen plant in the United States was funded by the DOE via taxpayer dollars (Schlissel et al. 2022).

These high costs will likely be recovered via higher utility bills for ratepayers, a regressive form of financing. For example, a study on the efficiency penalty of CCS for coal-fired plants found that electricity costs would increase by approximately 64% (Supekar and Skerlos 2015). Another analysis in Australia found that CCS would significantly increase wholesale electricity prices, and that the levelized cost of electricity (LCOE) for power generation with CCS is at least 1.5 to 2 times higher than alternatives like renewables with storage (Salt and Ng 2023). EJ communities already face disproportionately high energy cost burdens, paying a higher percentage of their total income toward their energy bills (Drehobl, Ross, and Ayala 2020), and an increase in electricity costs from CCS on its own or coupled with hydrogen production would exacerbate this existing injustice.

V. Conclusion

This paper has summarized evidence of risks and uncertainties posed by CCS and hydrogen co-firing deployed in the power sector that can negatively impact EJ communities in the United States. In synthesizing the best available data on equity, public health, safety, and environmental risks, we find that the potential harm to communities in close proximity to fossil fuel infrastructures where CCS and hydrogen may be deployed warrants reconsideration and a more thorough appraisal of carbon management strategies. CCS and hydrogen co-firing in the power sector could add to

cumulative burdens along their life cycles, from the points of fossil fuel extraction to combustion, transport, and use or storage. Contrary to a justice framework, impacts from all of the described safety, environmental, and health risks will likely fall disproportionately on low-wealth communities and Communities of Color, compounding existing burdens. Many of these impacts are yet to be fully evaluated or quantified, but any additional pollution burden in a community that already suffers from cumulative impacts is concerning from an EJ perspective. It is all the more difficult to accept such risks given the lack of evidence that CCS and hydrogen co-firing will actually deliver efficient and effective climate mitigation benefits. The potential for CCS and hydrogen co-firing to further entrench the fossil fuel industry and delay a real transition to renewable energy is itself an additional EJ concern, given the serious impacts that climate change has had and will continue to have on EJ communities.

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