Engaging Science, Technology, and Society

What Do We Mean When We Say Carbon Capture and Storage? STS and the Open Questions of a Technology in Emergence

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Abstract

Carbon sequestration is a relatively recent phrase that refers to a broad suite of technologies meant to minimize the amount of carbon emitted to the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) and many scientific organizations have recently emphasized that carbon capture is a necessary part of attaining net-zero or negative carbon budgets. It has also become a particularly controversial set of technologies, funding streams, economic proposals, and imaginations of energy justice in place. However, we—during our joint work as social scientists on the justice dimensions of one specific carbon sequestration feasibility study—have found that the dominating arguments for and against carbon capture erase the fact of its multiplicity. From our situated location, it seems an urgent time to ask, within a larger industrial decarbonization agenda, what are the specificities of carbon capture and storage and how might we (the collective 'we' of engaged researchers and thinkers with interests in science & technology or environmental and climate engineering) address them? In this *Engagement*, we sketch some of the ways in which STS brings important insights to the growing literature on carbon capture and storage (CCS) and, at the same time, what new directions carbon sequestration agendas might require of STS scholarship.

Keywords

carbon management; underground STS; climate change; geoengineering; environmental justice

Introduction

What is carbon capture and storage (CCS), and how ought we think about it? At a basic level, CCS projects entail removing carbon from air and pumping it underground, to be stored (aspirationally) for the geologic future. More broadly, CCS is emerging as a controversial set of practices and questions through which the fractures of different definitions of climate justice, sustainability, and responsibility fall out; the ever-expanding suite of "carbon management" technologies has become a polarizing issue across organizations, regions, and governments. For the Intergovernmental Panel on Climate Change (IPCC), carbon capture is now a requirement within carbon budgets that meet the goal of constraining climate change to 1.5 degrees Celsius of warming (Lahn 2021). To many climate professionals, it is a necessity in the "climate math" of

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attaining net zero emissions and an emerging technology requiring clearer regulatory guidance. To some environmental and climate justice groups, it is merely a "distractive technology" meant to lock in further fossil fuel investments. For carbon startups, it's a potential new market, and for some oil companies, it is a major new business model, allowing corporate structures to pivot toward low-carbon energy production. And these definitions coexist; none precludes the other.

But many of these arguments have to do with what we mean when we say CCS—depending on the "we" that is speaking, and with whom. An exclusive focus on the polarizing nature of carbon capture technologies elides the fact that these technologies—plural—are themselves in a process of definition and emergence. As others have similarly noted, STS is particularly well poised to investigate these questions within energy transition processes (Sovacool et al. 2020; Buck 2021b), given its intellectual capacity for analyzing technologies in emergence and shift rather than as static entities. At the same time, carbon capture—among the larger suite of climate engineering practices—is opening or hastening new research directions, approaches, and orientations for STS as a field. Therefore, in this short conceptual contribution, we discuss possible analytical contributions of STS toward a deeper understanding of CCS research and practice, including formations of gender, race, and social difference. In addition, we analyze what CCS technologies offer and ask of STS scholarship.

As part of a Department of Energy (DOE)-funded CCS feasibility study, we have been embedded in conversations about carbon management for the last three years. We were originally enrolled to conceptualize the "social impacts" dimensions of the study, given that the federal funding was originally accountable to former President Joe Biden's Justice40 initiative, which aspirationally directed federal agencies to channel 40 per cent of the benefits of these investments to communities that met statistical definitions for being classified as historically marginalized. One of us has written critically about how Justice40 formatted questions of environmental and energy justice in these projects as a whole (Smith 2024).

A full description of this process exceeds what we can articulate here, but for the purposes of this article, we note that our participation was also multiple. Our primary goal was to conduct community-based research, both to conceptualize the environmental justice and energy justice implications of a potential CCS facility, and to help ensure that these justice considerations were addressed in project development. This also meant, however, that we were frequently expected by other members of the project team to serve more as stakeholder engagement experts, with expectations of representing community concerns and—more nefariously—sharing emerging "stakeholder risks." We lived the tensions in the emerging carbon management industry that others might study at a distance, stoking our interest in questions such as: how are intentions to "do industry better" mobilized in carbon sequestration projects, especially given that CCS can easily (or already has) become simply a form of fossil-fuel greenwashing? How do place-based questions of economy and ecology interface with concerns for global carbon levels, and how are these questions sorted out by practitioners, regulators, residents, organizers, and academics?

Pursuing these questions entails sitting in interdisciplinary spaces where we are the only social scientists. It also entails sitting in the discomforts of conversations that often feel overdetermined from the start. Though CCS is still emerging as a set of technologies and imaginaries, it has become a particularly vexed fulcrum around which potent arguments over the most "just" and the most feasible way to address climate change collide. Talking about CCS never means only talking about CCS; as we regularly observed, questions of accountability, justice, and place-based visions of sustainable climate futures meet the often

disciplining and normalizing work of what is "rational," "possible," or "feasible." Suffice it to say here that part of the impetus for this article was precisely to sort out some of these questions from our own situated positions, asking how prior STS work might sharpen, complicate, or clarify our analysis. (Because our experience is grounded in working with the US Department of Energy and in southern Colorado specifically, our analysis of these confluences speaks most specifically to a North American context.)

At the same time, CCS offers new invitations to STS: from rethinking some of the common terms of contemporary STS scholarship to rethinking our roles as social scientists within a growing age of climate engineering. For instance, grappling with CCS is helpful in sharpening both the contributions and critiques of "extractivism" as a concept. It points to the significance of the affective dimensions of such processes, for their practitioners as well as others. And the "S" in CCS—storage—suggests an important set of vocabularies unearthing the implicit temporalities and planned uses within storage as a concept. This is not to say that this conceptual work is not already happening within STS—clearly, it is—but rather that CCS as an object of study crystallizes something about its urgency. In addition, CCS brings different STS areas of scholarship together; the juxtapositions of extractivism, climate aspirations, and imaginations of storage (rather than disposal) for waste offer a unique set of questions and concerns.

Rather than attempting a full review of the social science literature on CCS or the underground (see Buck 2021b, and Bosworth 2023, respectively), this article weaves together distinct threads, looking for new questions and new approaches to existing questions. First, in a familiar mode to many other STS analyses, we show that CCS is not a unitary set of technologies or expertise, but an emergent field that awkwardly draws together different sociotechnical systems, all animated by distinct (and even conflictual) visions of the future. Second, we argue that STS is uniquely positioned to intervene in how the harms and benefits of CCS are conceptualized, replacing bureaucratic documentation of "impacts" and "stakeholder outreach" with attention to the underground as a racializing and gendering formation. Finally, we argue that fully inhabiting the potential for STS scholars to inflect energy transition projects requires rethinking the role of STS scholarship and some of our core terms.

The Multiple Materializations of Carbon Management

Like other technologies, CCS is not one pre-existing thing. Instead, there are multiple, contested, emerging and evolving technologies, practices, and ideologies entailed in this short acronym, each of which draws on and will redefine complicated formations of social location, world-making, and belonging.

Carbon management involves both very old and very new technologies. Carbon capture and underground carbon injection have been practiced as "enhanced oil recovery" (EOR) since the 1970s. This involves pressurizing CO_2 gas to a "supercritical state," in which it behaves both as a gas and a liquid, to "push" additional oil from pore space (e.g., Kashkooli et al. 2022). EOR is a prime example of carbon capture used to support further fossil fuel production. Interestingly, some companies like Kinder Morgan currently extract CO_2 from naturally occurring underground formations for EOR, so shifting to using industrially emitted carbon instead represents a change in technology (Kinder Morgan n.d.). However, EOR is quite distinct from carbon storage; in EOR, only part of the carbon remains underground, making it a contributor to climate change rather than a mitigator (Ning and Tura 2023; Terlouw et al. 2021).

Carbon capture and underground injection started being conceptualized as possible "climate" technologies following the IPCC's (2005) special report on carbon capture and storage. The majority of high-

profile, currently debated CCS projects are industrial in nature and rely on point-source capture, using chemical or thermodynamic technologies to capture the CO_2 produced by burning coal or natural gas, producing cement, or manufacturing steel. A crucial question is where the carbon comes *from*, as the source raises questions of what industries it reinforces or extends. Each comes with a range of social and economic possibilities and consequences. For instance, even though capturing the carbon at a fossil-based power plant has technical efficiencies, it also comes closest to realizing fears that CCS serves as a smokescreen to prolong fossil fuels and their attendant social formations. In contrast, CCS can also be used to decarbonize "hard to abate" industrial sectors. Cement production, for instance, necessarily entails an output of CO_2 even beyond the power that it requires because of the mineral process of production itself. Finally, the prospect of bioenergy with carbon capture and storage has recently gained increased attention, which would use biomass to generate energy and then capture and store the resultant carbon dioxide emissions (e.g., Haikola et al. 2019, Hansson et al. 2022; Low and Schafer 2020).

Other technological processes do not rely on point source emitters. These include capturing carbon from ambient air (Direct Air Capture or DAC); storing carbon-rich biomass in the soil or marine sediments or converting biomass into bio-oils and biochar for storage (Biomass Carbon Removal and Storage); removing CO_2 from oceanwater (Direct Ocean CCS); and directing forestry and soil management to maximize carbon absorption. These technologies are at a much more experimental phase than point-source capture and may be less efficient, as the concentration of CO_2 in an effluent stream is much higher.

In recent years there has also been an almost frantic proliferation of experimentation for other uses for carbon, which adds the U of *utilization* to CCS (CCUS) with important ramifications:

> The shift from CCS to CCUS reframes CCS technology as a means for both using and storing the captured CO_2. This alters the valence of CO_2 from a form of pollution that must be captured for climate mitigation, to a commodity that can be used toward further fossil fuel extraction (Endres et al. 2016, 364).

CCUS proposals include processes that aim to use CO_2 alongside fossil fuels, such as sustainable aviation fuels (Abrantes et al. 2021) or supplementing fossil fuel feedstocks in plastic and petrochemical manufacturing (Lopez et al. 2023). Other potential uses also capitalize on the behavior of supercritical CO_2, including using its fluid flow properties in reactors, as a form of battery/energy storage, or to power turbines more effectively than steam (Jiang et al. 2025; Di Maio 2015). Others propose to use CO_2 in sealed greenhouses to stimulate plant growth (Bao et al 2018). One effort that combines several of these uses is the DOE's Mining Innovations for Negative Emissions Technologies program, which is experimenting with using CO_2 to increase the efficiency of mining for critical minerals like copper, lithium, and cobalt (Department of Energy n.d.).

However, many of these initiatives are fueled by the overabundance of carbon rather than a specific market demand for anthropogenic carbon-derived products, and substantial research on this front has been relatively stunted in comparison to sequestration. In addition, from a carbon reduction standpoint, the scale of carbon utilization that would be required to reduce atmospheric levels doesn't match with current demand for carbon or production levels, and careful lifecycle assessments are required to calculate whether a particular CCU project is carbon-neutral.

Even this brief sketch of carbon management activities emphasizes that it is a lively, emergent arena with significant implications for imagining future worlds, how we might imagine the forms of justice

and equity that are considered desirable, and addressing preconceived assumptions of what is feasible or reasonable. As many environmental NGOs and social science fields have shifted toward reluctant acceptance of some forms of CCS technologies, STS scholars have offered contributions to reflecting on and critiquing these shifts.

What Can STS Contribute to CCS?

Scholars working in and adjacent to STS have a range of diverse contributions to make to scholarship on CCS. For instance, a major thread of STS scholarship has increasingly analyzed "green transition" technologies, including CCS, with important insights for how to conceptualize the radical shifts and continuities entailed in different visions of a just transition. In addition to the role of mining for critical minerals and the production of large-scale renewable energy landscapes (Archer and Calvão 2024; Shokrgozar, Remme, and Stock 2024), major questions here include which carbon is being captured (Grubert and Talati 2024), and what political-economic structures this capture and transport supports (Deberdt and Le Billon 2024; Dunlap and Laratte 2022).

Others have investigated the sociotechnical aspects of carbon capture; while it can be imagined as only a technological question (and therefore technological solution) by many proponents, a sociotechnical approach brings more attention to the "epistemic, economic, technical, social, political, and environmental elements" entailed in decarbonization (Sovacool, Baum, and Low 2023, 57; Buck 2021a; Grubert and Talati 2024). These scholars have centered sociotechnical imaginaries of energy justice or decarbonization as a way of suggesting research agendas that are more "responsible" (Groves et al. 2023), "ethical" (Jenkins, Sovacool, and McCauley 2018), or contextualized in specific geographies (Richter et al. 2017).

One core question that has emerged here is around the role of what can be termed "community engagement," "community outreach," or "stakeholder engagement." Holly Buck, a scholar of geoengineering and carbon capture, for instance, articulates a kind of "double unseeing" in which climate professionals functioning within "expert sociotechnical imaginaries of the energy transition" (2021b, 3) emphasize net flows of carbon in which place-based impacts and issues remain unresolved—while publics focus on *local* issues and questions. The bulk of social science research thus far has focused on prospective public opinion or perception of CCS, asking about public understanding and relative support of CCS as a technology (e.g., Cox, Spence, and Pidgeon 2020; Shrum et al. 2020; Wolske et al. 2019; Nielsen, Stavrianakis, and Morrison 2022). At the same time, others have shown that there remains room for improvement in carbon professionals' communication with larger publics (Xenias and Whitmarsh 2018; Whitmarsh, Xenias, and Jones 2019; Einsiedel et al. 2013; Cecchini et al., forthcoming 2026).

We, for instance, have noted significant interest on the part of CCS projects in "doing community engagement right," and have found that because of our role as social scientists, others have assumed that our main job is social acceptance or community outreach work. Yet STS and the social sciences have much to add as fields of their own. This question offers a major avenue for STS' longstanding experience with the emergence of various technologies and scientific approaches as they emerge in place and with people. We argue that there are many directions in which CCS scholarship and practice could gain much from existing STS literature. Among the many possible directions, we sketch two below.

Defining and Understanding the "Underground"

Even though CCS is often thought about (especially among climate professionals) as a "climate math" question—one of atmospheric net balances—its sequestration is also a subterranean process that implicates deeply place-based questions (Buck 2021a), to which STS is directly poised to respond. Beyond the actual capturing of carbon, there is also the important question of where to *store* it, and this implicates understandings of the underground in important ways. We have each studied underground processes in various ways, from groundwater extraction to mining, and we believe that STS has a unique role to play here in conceptualizing the underground: as a rich site of STS inquiry, and as a place where the global questions of energy justice become irrevocably emplaced. STS already has robust tools for asking, for instance, what underground(s) are brought into being here—and through what "geosocial formations" (Clark and Yusoff 2017).

STS perspectives critique the static portrayals of the underground that circulate in CCS spaces. CCS boosterism describes carbon as being permanently sequestered in the ground through (predicted) mineralization. Positioning the underground as a permanent disposal site yokes bids at a planetary future with contestations over expertise and yet-to-be-developed grander timescale thinking (Ialenti 2020). This narrative is critiqued by scholars such as Kearnes and Rickards (2017) for an uninterrogated investment in the correcting work of the future. In addition, scholars have long shown that what we imagine as "the underground" never pre-exists; it is opaque, heterogeneous, and requires material work. The underground not only comes to be seen but comes to be in and through a range of interactions with technologies, humans and more than humans, emotional and affective investments, and more (Cumming 2018; Kinchy, Phadke, and Smith 2018; Marston 2024; Smith and Smith 2018; Underhill and Barad 2024). Here, STS can contribute approaches to the underground—not only conceptually but methodologically. Not only does underground STS offer tools to understand the underground aspects of carbon sequestration (underground-as-object), but it also helps theorize the multiplicity of CCS (underground-as-approach): just as the underground is multiple and emergent (Ballestero 2019; Lahiri-Dutt 2023; Bosworth 2023), CCS is also not one pre-existing thing.

In addition, STS approaches have highlighted the need to think beyond a simple surface/subsurface distinction. Instead, undergrounds require attention to the sedimentation of land use histories, affective relationships, and deep consideration of relationality. This orientation—"underground" not as static location but as complex and shifting sedimentation—provides important tools for analyzing localized questions and impacts of sequestration not separately from carbon transport and injection technologies, but as constitutively intertwined. It also belies the speculative futurisms (e.g., Haraway 2016) of permanent disposal within "techno-burial practices" (Kearnes and Rickards 2017; Ialenti 2020).

In other words, underground STS contributions are not limited to what is underneath the ground. STS literature has already offered a set of vibrant conversations on the ways in which the embodied and relational qualities of underground spaces are not asocial or beyond the social (though discourses of exploration and unavailability often frame them in this way) but rather have a way of *amplifying* the social practices and cultural milieu through which they come to be understood (Pérez 2021). This includes approaching gender, race, and other subjectivities as social formations in process, which come into being in and with environmental, planetary, and geologic transformations. These insights are directly applicable to the further role of STS in advancing ideas of "justice" described below.

Advancing "Justice" Amid the Racialized Geologic

STS is urgently needed to help theorize how CCS is embedded within racial capitalism. Many US CCS projects have depended on federal funding that bureaucratized "social impacts" (Schott and Whyte 2023; Smith 2024) in ways that did not recognize how the social forms of difference at stake (such as race, ethnicity, and gender) are always redefined, rearticulated, and co-constituted, as demonstrated by decades of scholarship across critical race and ethnic studies, Indigenous studies, and Black studies. Environmental justice scholars (e.g., Pulido 1996; Pellow 2016 and many others) have long shown that a flat description or observation of differential environmental impacts on pre-defined categories of race or class—such as those embedded in state and federal environmental justice screening tools—can risk flattening them into static and reified categories rather than formations in consistent flux (Underhill 2022; Horgan et al. 2024; Gutierrez et al 2021). Instead, they call for more rigorous theorizations of social difference. STS' approaches to how race, gender, and other forms of social difference shift, are re-defined, and re-articulated—especially with energy landscapes and technologies—have a major role to play here.

The co-constitutions of emerging CCS technologies with shifting formations of race, gender and nationality come to the surface in the slippages from the specificities of *where* and for *whom* carbon is emitted to its generalized atmospheric circulation—and back to the specificities of *where* and *under whom* might it be sequestered. For example, in the case of our study context, the proposed wells are under rural ranching lands, and the study would have investigated CO_2 transported there with pipelines that would traverse the city of Pueblo, a historic steelworking center that already experiences disproportionate environmental hazards in relation to the rest of the state. Its residents' racial and ethnic diversity represents the streams of migration from across the country to work in its mid-20th-century steel economy. Coal and natural gas power plants' air quality impacts layer on top of the long-term impacts of the smelters' heavy metal contamination, all of which disproportionately impact the city's historic Latinx neighborhoods and low-income residents (Diawara et al., 2018; Martenies et al. 2019). Meanwhile, the nearby ranchers articulate a very different set of investments, including generational (mostly settler) attachments to specific land and the groundwater it requires, and suspicion of "green" techno-promises, including the nearby encroachment of mega-solar fields. The complexities of this area's history, and its co-constitutions with proposed underground sequestration, far exceed a simplistic idea of "geologic processes and projects" on the one hand and "underrepresented groups" being impacted on the other, as if each were pre-existing, isolated, and static formations. Instead, they point to a much more complex set of dynamics in which the literal grounds (metaphorically and figuratively) of geologic processes are definitionally circumscribed by these racializing histories.

One of the largest literatures through which these co-constitutions have been theorized is investigation of the extractive industries fueling various energy forms, from coal and mineral mining (Bell and Braun 2010; Voyles 2015; Smith Rolston 2014; Yusoff 2015) to oil and gas (Watts 2012; Appel 2012; Cumming 2018) to groundwater extraction (Zwarteveen et al. 2021; Rudestam, Brown, and Langridge 2018; Underhill et al. 2023; Kroepsch 2018). Much work has also been done on the exploration and measurement of the underground as a mode of claiming and maintaining settler colonial sovereignty or imperial expansion (e.g., Hoogeveen 2015), related to the work of staking underground "claims" for geopolitical power. And the small but growing study of speleology and cave cartography (Mattes 2015; Cant 2006)—from Cuba (Pérez

2021) to Mexico (Melo Zurita 2019) to China (Shen 2014)—has consistently highlighted the emotional and affective ties between people and their undergrounds.

In addition, a rich and growing body of scholarship at the intersection of Black feminisms and STS interrogates the co-constitution of racial difference with geologic knowledge, ideas of earthly matter, and the distinction between human subjectivity and inert matter. Drawing on anticolonial critic and philosopher Sylvia Wynter's seminal work (e.g., Wynter 2003) articulating the genealogies through which the category of the human-as-Man was produced precisely through its constitutive exclusions, others have also pointed out the constitutive exclusions of living/nonliving (Povinelli 2016), flesh/subject (Weheliye 2014), object/matter vs subject (Hartman 1997; da Silva 2017), and animate/inanimate (Chen 2011) as similarly racializing distinctions requisite to contemporary ideas of human subjectivity and of geologic matter (Jackson 2020; McKittrick 2006). Others have also articulated how geologic knowledge itself is based on and grew through radical differentiation (Cohen 2022; Quintana-Navarrete 2022; Marston 2024; Yusoff 2018; Yusoff 2024). Yusoff (ibid., 10) recently articulated how "race is foundational to the production of knowledge about the earth within a Western episteme," and that geology is "foundational to racial violence and the possibilities of place."

While geologic race produces differentially valued bodies, the growing field of discard studies investigates ideas and practices of waste or making waste as a central aspect of making and maintaining social, economic, and political power (Liboiron and Lepawsky 2022). What is considered waste or wasted is always gendered and racialized; in addition, the practice of disposing of waste often holds important connotations of purifying what remains as not-waste (Kearnes and Rickards 2017). STS scholars have made important contributions here (Millar 2018; Alexander and O'Hare 2023), not least around the ideas of particular ecosystems as "wasteland" that are available to receive waste or to be "wastelanded" (Voyles 2015). In our study context, the idea of waste is a continuously animating concern: some CCS proponents have described the open prairie land as "nothing but sage grouse out there," but local ranchers and environmentalists vehemently disagree with the assertion that there is "nothing there" and that, therefore, the land and its undergrounds are available for industrial-scale sequestration. Meanwhile, though Pueblo is deeply supportive of continued industrial production, its residents also resent being an ongoing "dumping ground" for both the coal-based energy production and carbon sequestration that the rest of the state's energy needs require.

Some CCS research is already attending to the ways in which emerging CCS economies impact existing environmental injustices and exacerbate existing racial inequalities (Tyree and Greenleaf 2009; McLaren 2012; Batres et al. 2021). But there are also questions for STS to ask not only about how the benefits and harms fall out along these lines, but how the lines of race, gender, place, and belonging are themselves maintained and reshaped. Across these diverse STS engagements with racialization and gendering processes, we see a rich opportunity for CCS work to deepen its theoretical frameworks around not only the raced and gendered impacts of its harms and benefits, but its role in the shifting and re-articulating of social difference more broadly.

What Does CCS Ask of STS?

CCS technologies, within the larger landscape of energy-transition technologies, are also offering new contexts of generative difference, demanding new and different analyses and approaches from STS and its

adjacent fields. CCS is very much an object of its time, in that the slippages it holds signal some of the shifting structures/landscapes of this present moment. In that sense, its concerns also serve a diagnostic function. We argue that CCS points to potentially important future directions: first, in terms of present reformulations for STS and its core terms, and second, in terms of the role that STS scholars might take up in the emerging energy transition.

What Do We Need of Our Core Terms?

CCS is pushing some of the field's core terms to move and change—even terms which have been already deeply theorized. For instance, STS has long focused on the dynamics of extraction projects (e.g., Jalbert et al. 2017; Gómez Barris 2017; Mitchell 2013; Wylie 2018; Li 2015; Voyles 2015). As an analytic tool, extractivism draws attention to how turning "nature" into "resources" unjustly distributes profits and what Szeman and Wenzel (2021, 511) summarize as a "human instrumentalization of nonhuman nature."

Extractivism is also, unsurprisingly, a core way in which CCS has begun to be theorized. Similar sets of actors, expertise, corporate techniques, and financial and material infrastructures between CCS and oil and gas add to the appeal of comprehending carbon storage through the lens of extractivism (e.g. Alexander and Stanley 2021; Nicholson 2021). While CCS could be seen as extractivist simply in the fact that it is premised on commodifying carbon and pore space as resources, most interpretations of CCS as extractivist primarily hinge on its service as a "legitimizing technology" that contributes to "perpetuating and normalizing extraction" of fossil fuels (Alexander and Stanley 2021, 3). Noting "interdependence" between CCS and the oil and gas industry, Grubert and Talati (2024, 3–4) argue that market-based CCS "implicitly and explicitly benefits from the ongoing use of fossil fuels and fossil fuel infrastructure, both directly (for fuel and storage resources) and indirectly." However, taking a cue from the growing "green extractivism" literature (e.g. Deberdt and Le Billon 2024), CCS could also be interpreted as extractivist if it uses resources while concentrating wealth elsewhere, even if CCS is deployed in ways that do not perpetuate fossil fuel production.

Yet extractivism may be a blunt analytic tool for grappling with CCS. Szeman and Wenzel (2021) caution against using extractivism as "the name for any process through which value is generated for capitalism" (510) and call for scholars to consider the "variety of social relations constellated around different kinds of resources" and "how these different resources and relations register in, or otherwise intersect with, cultural production" (511). Rather than presuming that all mining is inherently harmful, Ureta and Flores (2022) examine the relations among humans, minerals, environments, and other beings as one of "geosymbiosis" that can range from mutualistic to parasitic and toxic.

While STS literatures have already been moving in this direction, CCS offers a new demand and urgency for thinking through our conceptual terms because it is a very different sociomaterial practice than resource production, even though CCS comes along with many of the same concerns and fears that scholars have previously identified through languages of extractivism. The question, essentially, is: though there is something important to articulate in the pull to deem CCS as extractivist, can we instead find sharper analytical tools, ones that better comprehend the specificities of its emergence?

Extractivism especially fails to grasp the *affective* dimensions of engagements with the underground illustrated in cases as diverse as cavers (Pérez 2016) to oil and gas professionals (Smith and Smith 2018). For instance, in the case of our own research project, CCS scientists, engineers and other

professionals hold powerful senses of optimism and certainty in the potential for CCS to "save the climate." Understanding why and how these interpretations propel the industry, beyond PR and talking points, is crucial. Employees' own emotional and subjective interpretations of their work can point us to these dynamics, but studies of CCS professionals as embodied people, enmeshed in relationships and ethical dilemmas, remain relatively rare. Holly Buck (2018) importantly profiles key scientists who are attempting to do CCS differently—to bring about more just and ethical futures. Environmental humanities scholar Endres and colleagues (2016) explore everyday expert-to-expert communication among scientists during the shift from CCS to CCUS framings of their work. They find that even skeptical scientists couldn't resist the change in framing because their employers and granting agencies had already adopted it (365).

Finally, the "storage" of CCS rather than the "extraction" of minerals necessitates new analytic terms that are nevertheless attentive to the major concerns already extant within extractivist research. Anthropologist and computing scholar Sean Field (2024) argues that the storage dimension of CCS serves as a strategy for industry to outwardly project good governance. Sayd Randle, anthropologist of water storage (2022), has applied it to groundwater storage and extraction in the US West, showing the increasing importance of storage for urban environments in the face of climate change. In addition, the theme of energy storage is increasingly at play in mining companies' attempts to rebrand as "sustainable" through the need for critical minerals in decarbonization plans (Archer and Calvão 2024).

Unlike other cases of storage, however, the carbon in CCS is explicitly not being stored for future use; unlike vaccines or toilet paper (during the Covid-19 pandemic), it is not being hoarded for a time when it will be more valuable. Unlike groundwater, it is not being stored for a time when its use will somehow bolster national, regional, or individual "security." Carbon storage is not imagined as protection from future scarcity, but rather protection from future (and present) overabundance. Moreover, many scholars and practitioners argue that carbon sequestration is better conceptualized as waste *disposal* rather than storage (e.g. Buck 2019). Many of the carbon professionals we observed implicitly noted this as well: it has more in common with oil and gas wastewater disposal than it does with temporary storage.

Storage also brings different temporal horizons to questions of the Anthropocene (Ialenti 2020). For CCS, the temporality at play most often features a bid for the future, underpinned by carbon professionals' investment in the underground as a site of hope or salvation; whether that future is one that extends fossil fuel use or attempts to protect life on earth itself (or both at the same time) depends on who is doing the imagining. Interestingly, in the earlier decades of CCS research stemming from the IPCC's original (2005) report, storage was assumed to be an easier problem to address, based on assumptions of enough underground pore space to hold thousands of years of carbon storage. Now, as estimates of the necessary storage have significantly increased, storage has returned as a bottleneck once more (Hansson et al 2022; Grubert and Talati 2024).

In one particularly insightful example, oceanographer David Ho (2023) points out that—at current carbon emissions levels—current storage capacity would only turn back the climate clock 13 minutes per year. But, in a future where emission levels are assumed to have decreased, the same storage capacity represents a much larger fraction of total emissions and could turn back the clock of yearly emissions in years rather than days. In other words, storage within CCS invites a new and surprising set of calculations converting pore space to time. The slipperiness of storage will have important ramifications throughout

energy futures, not only regarding carbon, but the many other storage/disposal needs of nuclear waste and other future energy technologies.

Reimagining Our Role

Critiques of extractivism also circle around the question of precisely what and where the possible modes and points of STS interventions are. In terms of extractivism, Szeman and Wenzel write, "After such naming, then what? Out in the world, the digging continues" (Szeman and Wenzel 2021, 517). This provocative phrasing, they write, is "not to say that critical or pedagogical work has no effect," (ibid.) but to think carefully about the political and pragmatic interventions that such critical interrogations aim for in their scholarly and activist interventions. This question, we believe, remains equally important in investigations of carbon sequestration and decarbonized energy futures.

For instance, CCS demands a new set of conversations among STS scholars over the role of our scholarship and institutional affiliations. As new private–academic partnerships are taking shape, social scientists are increasingly being enrolled into major federally funded, multidisciplinary, multi-sector decarbonization projects (Hirsch et al. 2024). Though this was clearly evident at the time of our initial writing in 2024, this point's importance has only grown in the last months; at the time of this essay's final revisions in 2025, these partnerships are being profoundly revised based on major shifts in the federal landscape. While most STS interventions have remained in the interpretive vein and have tended to "shy away from the necessary work of intervening and reflexively engaging with systems, institutions, and practices of participation" (Chilvers and Kearnes 2020, 350), this moment requires a different orientation to our role. STS scholars can no longer "sit on the sidelines" of the energy transition (Sovacool et al. 2020, 15) but must actively become "critical participants" (Downey and Zuiderent-Jerak 2021), using the critical and collaborative tools the field has spent decades developing. This both invites major questions about the role of social science researchers within the energy transition and offers new research avenues and approaches (Hirsch et al. 2024). But how ought we participate, especially when projects at scale involve "collaborating" with major utilities, private corporations, and federal agencies that are otherwise the subject of strong STS critique? We ourselves have experimented with this question through our work on the CCS feasibility study and in our conversations with similarly positioned social scientists. In particular, we find that strong commitments to "community engagement" would benefit from a deeper set of questions about power, agency, and the inheritances from industry pasts.

We are keenly aware that "participation" itself can be a depoliticizing move (Kelty 2020), and that calls for dialogue and collaboration can privilege the already powerful (Ottinger 2013)—a sober reminder when social scientists are positioned as contributors to rather than as intellectual leaders of joint projects with STEM-trained researchers and corporate developers. One of the major strengths of STS research has always been rigorous frameworks to study the underlying structures of thought between different scientific practices, and emerging research is addressing this question directly (Shrum et al. 2020; Ferguson and Ashworth 2021; Jenkins, Sovacool, and McCauley 2018). Emerging energy futures will only increase our need for work attuned in this way.

Conclusion

Ultimately, CCS—where, materially, the urgency of climate mitigation meets geologic strata and industrial histories of extraction—is rich with questions and implications that inform how CCS unfolds at all: as a process of transforming places (of many scales), ourselves, and others. The inflections of CCS and STS are many, from the crucial role of STS scholarship in this field to the need to rethink the role of the social sciences within the demands of a future climate. Here, we have argued for the importance of STS' analytical tools to think clearly about emergent CCS technologies and imaginaries; the emerging landscape of decarbonized energy technologies will benefit from STS' engagement with the underground, community engagement, discard studies, and likely others. In addition, we have pointed to how the demands and requests of our "critical participation" in CCS experimentation pushes key STS analytic terms and modes of scholarship. The multiplicities that already inhere in carbon capture point to the formative role of many different visions for CCS within many different energy futures—and the tensions between them.

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