How Much New Forest Land Would It Take to Offset a Coal Plant's Greenhouse Gas Emissions? *An Engineering Case Study of Georgia's Plant Scherer*

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ABSTRACT Climate change is largely caused by continued use of fossil fuels to provide energy services. Increasingly, given the goal of mitigating climate change, organizations like power utilities are announcing "net-zero" greenhouse gas (GHG) emissions goals that do not necessarily require fossil fuel–fired facilities to mitigate their emissions or close. If paired with carbon dioxide removal (CDR), ongoing emissions could theoretically coexist with net-zero goals. CDR, however, is resource intensive, regardless of removal pathway. One common question is whether tree planting could be a low-impact pathway to compensate for ongoing or legacy GHG emissions, since trees take up atmospheric CO_2 and store the carbon as wood. Although planting trees might sound like a benign climate strategy, the need for additionality and permanence means that forestry-based CDR has immense land requirements at climate-relevant scales. To contextualize this land intensity, this case study evaluates how much land would be required to counterbalance a utility's emissions from a large coal-fired power plant in Georgia with forest-based CDR. Compensating for 1 year of plant emissions would require permanent industrial forestation of all land in the plant's host county that is not already forested or developed (with buildings, roads, etc.), with a 30-year lead time—highlighting a key challenge of relying on tree planting to meet climate goals. Readers engaging this case will be able to discuss land use requirements of relying on compensatory forestry-based CDR for net-zero emissions goals, in addition to being prepared to replicate this analysis for other power plants or emitters. KEYWORDS forestation, decarbonization, coal, net zero, carbon dioxide removal

INTRODUCTION

Climate change is largely caused by combusting fossil fuels, which converts the stored fossil carbon to carbon dioxide (CO_2). Carbon is the basis of life on Earth, including the prehistoric swamps and marine organisms that have become coal, fossil natural gas, and oil. CO_2 that results from burning these fuels in energy systems, which combines carbon and atmospheric oxygen to make CO_2, is the most significant anthropogenic driver of climate change [1]. Coal has the highest combustion CO_2 emissions per unit of energy, though natural gas can have overall greenhouse gas (GHG) emissions approaching or occasionally surpassing coal emissions due to methane emissions, which cause more climate change per unit mass than CO_2 emissions [2–4].

U.S. fossil fuels account for about 80% of total marketed primary energy consumption, providing energy services like transportation, direct heat, and all of the services for which we use electricity [5]. In the United States, the largely fossil fuel–based energy system emits about 80% of official 2019 GHG inventoried total emissions (gross; excluding influence of GHG sinks) as CO_2 equivalents on a 100 year basis, a measure that accounts for the varying radiative forcing power of different GHGs like methane and nitrous oxide (N_2O). The vast majority (~90%) of these fossil fuel system CO_2-equivalent emissions are CO_2 from burning fossil fuels [6]. Other GHG emissions are from sectors like industry and agriculture [6], which often produce GHG emissions that are considered difficult to eliminate in part because they are fundamental to the processes. For example, calcination processes for cement production drive CO_2 off the input materials [7], and nitrogen fertilizers used for agriculture can lead to N_2O emissions [8]. By contrast, because

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usable energy carriers like electricity can be made from a wide variety of energy resources—including those that do not produce CO_2—the energy sector is considered to be relatively easier, though not easy, to decarbonize [9].

The electricity sector is widely considered to be a critical enabler of decarbonization, through a combination of decarbonizing electricity production itself (e.g., by using wind and solar instead of coal and natural gas to make electricity) and using electricity to provide a wider variety of energy services (e.g., providing transportation via electric rather than gasoline vehicles) [9]. Such decarbonization means a transition away from the fossil fuel–dominated energy system [10]. In the U.S. electricity sector, this transition largely means retiring or controlling emissions from coal- and natural gas–fired power plants (oil fuels a very small proportion of U.S. electricity generation, usually in places where alternative resources are very expensive [e.g., Hawaii] or where petroleum-derived fuels are relatively cheap [e.g., as refinery byproducts]).

GHG emissions are not the only pollutants associated with burning fossil fuels, and many of these other pollutants have been regulated for much longer due to their negative impacts on health and the environment. Environmental regulations focused on power plants have traditionally targeted these non-GHG pollutants, like the precursors of acid rain and smog [11]. Investigating how power plants have complied with these earlier requirements is one way to identify how they might approach decarbonization goals and requirements. For example, strategies for complying with clean air regulations have historically included fuel switching, installation of pollution control equipment like scrubbers, or paying for reduced emissions elsewhere in the system. Some fuel switching results in plant retirements or complete rebuilds, which are essentially retire-and-replace strategies, for example, for switching from coal to natural gas. Other fuel switching might require less complete retrofits, as when higher and lower sulfur coals are blended in the same plant to meet specific emissions requirements. Scrubbers are generally not 100% effective but can reduce emissions below required regulatory thresholds. Paying for emissions reductions elsewhere in the system is the basic principle behind cap-and-trade, a market-based approach that has notably been applied to reduce acid rain emissions in the United States since 1995 [12].

Given their role as major GHG emitters, and given increasing expectation that the electricity sector's GHG emissions will be regulated [13], many electric utilities are now investigating approaches for managing CO_2 emissions that will likely include these same basic strategies. A new challenge, however, is that unlike most prior air pollution regulations, GHG emissions regulations and goals have a target of no, rather than lower, emissions—something reflected in increasingly common "net-zero GHG emissions" targets by utilities and other organizations. This target of zero means that fuel switching requires more fundamental shifts (e.g., coal to wind rather than bituminous coal to subbituminous coal), pollution controls (e.g., carbon capture and storage [CCS]) that are not 100% effective are insufficient, and trading for emissions reductions elsewhere in the system while continuing to emit at the original facility cannot enable net-zero emissions. In many cases, electric utilities' net-zero goals appear to be more ambitious than emissions reductions commitments to date [14], which prompts the question: Are utilities considering options beyond emissions reductions?

Although paying other system actors to reduce emissions in exchange for continuing to emit is not sufficient to reach zero emissions, emissions can be offset, or canceled out, if CO_2 is actually removed from the atmosphere through carbon dioxide removal (CDR; for a detailed overview of CDR, see [15]). This is the principle behind "net zero," as opposed to "zero" emissions: A positive emission plus a negative emission results in a net-zero emission (CDR is sometimes also called negative emissions technologies [16]). Removing CO_2 means capturing CO_2 from the atmosphere and permanently preventing it from reentering the atmosphere, usually by storing it geologically, biologically, or in products like mineral aggregates that do not release the CO_2 again. For an activity to be CDR, removals must be intentional, additional (i.e., would not have happened but for the CDR intervention), and permanent if they are to effectively compensate for ongoing emissions in a net-zero context. Ensuring that CDR leads to true removals is particularly important because assuming CDR is or will be available at scale and reasonable cost might reduce the perceived urgency and importance of reducing emissions directly [17]. For utilities, the mismatch between net-zero goals and emissions reduction plans implies potential reliance on CDR, despite widespread assumptions that CDR is likely to be sufficiently costly and socioenvironmentally constrained that it should be reserved for the hardest-to-decarbonize activities, including addressing legacy emissions [18–20].

CDR pathways span a spectrum of approaches, from more technological approaches like direct air capture and storage (DACS), which relies on chemical separation of CO_2 from the atmosphere followed by storage underground or in products, to more biological approaches like increasing standing forest carbon. Biological approaches focused on enhancing or expanding natural carbon sinks, like ecosystem enhancement, ecosystem restoration, and increased forest cover, are sometimes seen as relatively more benign or potentially positive than approaches that require isolating and controlling a fluid CO_2 stream for management (e.g., biomass carbon removal and storage, enhanced weathering, DACS), which are costly, energy intensive, and carry few potential environmental cobenefits beyond their CDR impacts [19]. As such, these biological approaches are often highlighted as potentially desirable mechanisms for reaching net zero, though they, too, face challenges. In particular, demonstrating additionality and permanence are especially important in cases where interventions are meant to enhance processes that are already happening and can be easily reversed, like biological CO_2 uptake. According to the official inventory of U.S. GHG emissions, natural carbon sinks—collectively referred to as land use, land-use change, and forestry—absorbed GHGs equivalent to an estimated 12% of U.S. CO_2-equivalent emissions in 2019 [6]. These carbon sinks, however, are not CDR even though they do remove CO_2 from the atmosphere, because they are not intentional or additional. Further, they are highly subject to reversal through mechanisms like fire, decay, and land disturbance. As such, any biological CDR needs to be both additive and carefully monitored.

Assuming careful attention to baselines, creating or optimizing natural carbon sinks can be CDR when appropriately designed, measured, and verified [15]. Probably the best known and most easily quantified method is afforestation and reforestation, which we refer to collectively as "forestation" in this piece. Trees take up CO_2 and store it as wood carbon, thereby removing it from the atmosphere. The capture and sequestration steps are the same step (i.e., plant uptake), though care must be taken to prevent the CO_2 from reaching the atmosphere again at the end of the plant life cycle. Although there are other proposed nature-based CDR approaches, like coastal blue carbon (often achieved through wetland restoration) and soil carbon sequestration (often achieved through carbon-oriented land management methods), we focus specifically on forestation because it is a demonstrated industrial process, though it has not typically been deployed specifically for CDR in the past. As with any large-scale intervention, forestation faces numerous challenges. In this case study, we investigate just one, which is the land intensity of using forestry-based CDR. Specifically, we ask: How much land would it take to use forestry-based CDR to compensate for one utility's CO_2 at a large coal-fired power plant in Georgia, with the goal of reaching net-zero emissions?

CASE EXAMINATION

For this case study, we evaluate Plant Scherer, which is a large coal-fired power plant in Monroe County, Georgia, operated and part-owned by Georgia Power, itself a subsidiary of Southern Company. Plant Scherer, which burns subbituminous coal imported from Wyoming [21], emitted roughly 13 million metric tons of CO_2 in 2019 [22]. This level of emissions is about the same as the energy-related CO_2 emissions from the state of Delaware or Rhode Island and about 10% of the total energy-related CO_2 emissions in the state of Georgia, including from cars and trucks, gas heat, and electricity [23]. Georgia Power's share of Plant Scherer accounts for about 10% of its emissions from owned assets as of 2019 [24].

At 3,564 megawatts of nameplate capacity, Scherer was the highest capacity coal plant in the country in 2019, though it is expected to lose that title to another Georgia Power coal plant, Plant Bowen, in 2022 when partial owner Florida Power & Light retires Scherer's unit 4 [25, 26]. In 2007, when Scherer's emissions were about double what they are today (due largely to higher capacity factor, at 80% in 2007 vs. 49% in 2018 [27]), the plant was the only U.S. power plant included on the global top 25 CO_2 emitters list, at number 20 [28]. Figure 1 shows a satellite image of Plant Scherer, which is about 125 km from the authors' home institution, the Georgia Institute of Technology in Atlanta.

Through its parent company, Southern Company, Georgia Power has a goal of net-zero GHG emissions by 2050 [29]. Although there are no formal requirements to decarbonize in the state of Georgia [30], as of 2021, the federal government has declared a goal of reaching zero GHG emissions in the electricity sector by 2035 [13], much earlier than Southern Company's

Figure 1. Plant Scherer, Monroe County, Georgia. Satellite image of Plant Scherer, the U.S.' largest coal-fired power plant by capacity as of 2019. Imagery and Map data via Google: (c) 2021 Maxar Technologies, U.S. Geological Survey, USDA Farm Service Agency. Used with permission (https://about.google/brand-resource-center/products-and-services/geo-guidelines/).

commitment. As such, we expect that some action to decarbonize Georgia Power's system is coming. To reach net zero, Georgia Power has multiple options, similar to those that utilities have historically faced for air pollution: (1) use different fuels, which for GHG controls likely means retiring fossil fuel–fired units or retrofitting them to burn alternative fuels like biomass; (2) add pollution controls that will eliminate GHG emissions, a major challenge given that postcombustion CCS technologies have not been demonstrated to fully eliminate GHG emissions [31]; and/or (3) create or purchase the right to claim emissions removals elsewhere, as with CDR.

In Southern Company's net-zero announcement, the company indicated that it would pursue both direct emissions reductions and CDR approaches to reach net zero [29]. Although no fossil fuel–fired power plants in Georgia, including Scherer, would be expected to still be operating by 2050 assuming typical historic life spans [10], Georgia Power had no formal, public plan to pursue full direct emissions reductions at Plant Scherer (e.g., via retirement or retrofit) when the net-zero goal was announced [25]. (We note that in November 2021, Georgia Power announced its intention to retire Unit 3 at Plant Scherer by 2028 to comply with effluent limitations [32]; it is a minority owner in Units 1 and 2 [table 1].) Simultaneously, Georgia is a major forest products state with high biomass productivity, so local forestry-based approaches to climate action are frequently proposed as a way to take advantage of local natural and industrial conditions (e.g., [33, 34]). Thus, as a thought experiment, given Southern Company's statement that CDR might be part of its net-zero strategy, this case study evaluates the land use implications of relying on forestry-based CDR to counterbalance Georgia Power's CO_2 emissions from Plant Scherer instead of retiring or retrofitting the plant. The objective of this study is to estimate the land area that Georgia Power would need to commit to forestry-based CDR to achieve net-zero emissions from the plant by 2050 using forestry-based CDR alone, that is, to remove CO_2 at the same rate at which it releases it into the atmosphere. The secondary goal of this analysis is to contextualize this land use assuming only local (which we define as in-county or in-state) land can be committed to CDR.

Table 1. Plant Scherer and Georgia Power Ownership Data, 2019.

Unit	Capacity (MW, 2019)	Net Generation (Million MWh, 2019)	Georgia Power Ownership Share (2019; %)	Georgia Power CO_2 Emissions (Million Tons, 2019)
1	891	2.6	8.4	0.24
2	891	2.9	8.4	0.26
3	891	2.6	75	2.1
4	891	3.9	0	0

Source: Data from [21].

CDR for Plant Scherer

In order to quantify land use requirements for compensatory forestry-based CDR for Georgia Power at Plant Scherer, we require two key pieces of information: (1) CO_2 emissions per year from Georgia Power's share of Plant Scherer and (2) land intensity for forestry-based CDR per unit of CO_2 emissions removed. From these data, total land requirements can be calculated as

$$\frac{\text{land area for compensatory forestry-based CDR}}{\text{year of plant operations}} = \frac{\text{plant } CO_2 \text{ emissions}}{\text{year}} \times \frac{\text{forested land area}}{\text{cumulative } CO_2 \text{ removed by year}}.$$

The next sections describe how each of these elements was computed, in turn.

ANNUAL CO_2 EMISSIONS FROM GEORGIA POWER'S SHARE OF PLANT SCHERER

We begin by estimating annual CO_2 emissions from Georgia Power's share of Plant Scherer. U.S. power plants report substantial operational and ownership information that is reported annually by the federal Energy Information Administration (EIA), which means that internally consistent, frequently updated, and publicly available information is available. To estimate annual CO_2 emissions from Georgia Power's share of Plant Scherer, we need to know (1) what equipment constitutes "Plant Scherer," that is, which generating units are in scope, (2) how much of that equipment is owned by Georgia Power, our utility of interest, and (3) the volume of CO_2 emitted by Georgia Power's share of the equipment each year. Item 3 is the most complex, as CO_2 emissions are neither reported at the generating unit level nor static from year to year. Relevant emissions for a given historical year can be allocated to a specific utility using a combination of annual data reported by EIA: unit-level ownership, unit-level generation, unit-level technological characteristics that drive emissions intensity (fuel, like natural gas or coal, and prime mover, like combustion turbine or steam turbine), and plant-level emissions by fuel and prime mover. Note that this approach assumes that units with the same fuel and prime mover have identical emissions intensity. Figure 2 shows the calculation approach.

Translating historical emissions to future emissions requires an assumption about future conditions. For this exercise, we follow [10] and assume Georgia Power continues to indefinitely operate its share of Plant Scherer at 2019 levels—that is, annual generation and emissions remain constant, and Georgia Power does not retire any of its ownership share of the plant. In practice, annual generation per unit of capacity has been falling over time at U.S. coal plants, including Scherer [27], and as noted above, Unit 4 is expected to retire in 2022 and Unit 3 is expected to retire by 2028. Here, we assume Scherer maintains 2019 outputs as an illustrative counterfactual to evaluate forestation-based CDR rather than retirement or other alternatives as a decarbonization strategy.

Using the flow shown in figure 2, using federally available data from EIA 860 (capacity by unit, Schedule 3_1; ownership by unit, Schedule 4) [35], EIA 923 (generation by unit, Page 4) [21], and EIA's "Emissions by plant and by region" data (CO_2 emissions by plant) [22] for 2019, we find that Georgia Power would be responsible for removing 2.6 million tons of CO_2 per year of operation to counterbalance continued operation of Scherer using CDR, assuming ownership of 818 MW and 2.4 million MWh annual production, with total plant emissions of 13.1 million tons [22]. Table 1 summarizes our assumptions, using metric tons. For context, total combustion emissions from fossil fuel–fired power plants in Georgia was about 51 million tons in 2019 [22].

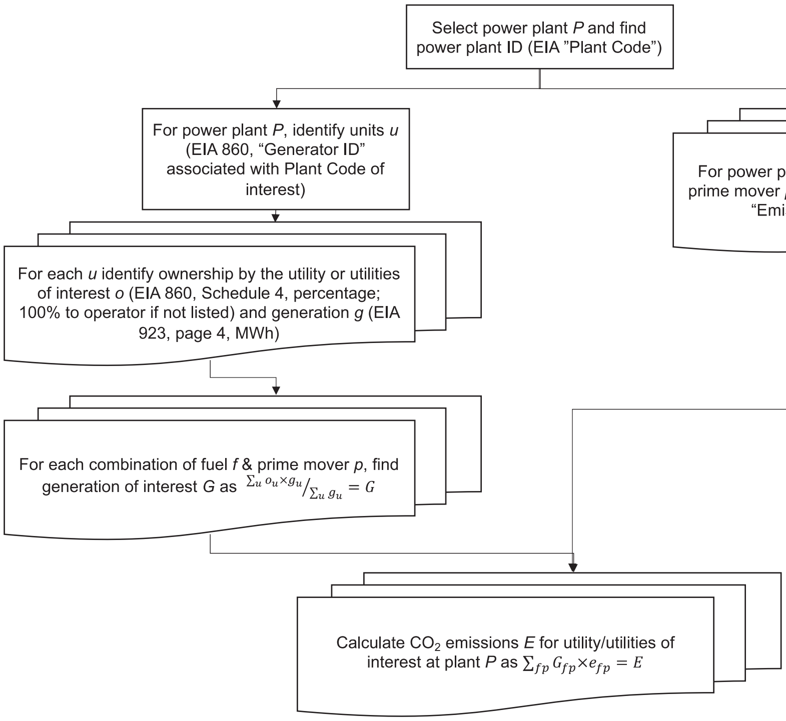

FIGURE 2. Flowchart logic for calculating annual emissions for a given utility at a given U.S. power plant.

Land Intensity of Forestry-Based CDR

We next estimate the amount of CO_2 that could be removed per unit of land in Georgia that is newly forested and maintained for CDR purposes. Forest CO_2 uptake varies based on location, and due to our specific interest in using local (same county or same state) land for CDR, we investigate land intensity per unit of CDR that would be expected locally. Using a 2006 study by the U.S. Department of Agriculture, Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States [36], we identify the highest available resolution geography, which in this study is the Southeastern United States. This document includes estimated carbon storage over time (in tons carbon per hectare or acre) for multiple forest types in the Southeastern United States: loblolly-shortleaf pine (including high productivity, high intensity management; Tables A39–40), longleaf-slash pine (including high productivity, high intensity management; Tables A41–42), oak-gum-cypress (Table A43), oak-hickory (Table A44), and oak-pine stands (Table A45). Using this resource and the molecular mass ratio of 44/12 to convert carbon to CO_2 mass, we calculate estimated change in total forest carbon density over time, assuming forests are planted on clear-cut land (figure 3).

Figure 3 shows CO_2 uptake over 90 years, with the S-shaped growth curve characteristic of vegetative carbon density [37] most visible for the high-productivity, high-intensity management loblolly-shortleaf pine and longleaf-slash pine forests [36]. By comparing the high-productivity, high-intensity management forests with typical conditions for the same type of forest, we observe that the CO_2 uptake over 90 years is essentially the same as is achieved in 30 years under high-intensity management, so assume this end value is a reasonable estimate for total possible CDR in steady state. We assume, very optimistically, that forest planting and management results in no additional CO_2 emissions (e.g., from trucks used for planting and maintenance) and that forest carbon is permanently stored (e.g., is not lost to wildfire, pests, or other death without instantaneous total replacement), so total removals are equal to total forest carbon. Using the values for cumulative tons of CO_2 uptake per acre (total nonsoil), which range from about 170–240 cumulative tons per acre (figure 3), achieved in 30 years for the high-productivity, high-intensity management stands and in 90 years for others, we then estimate the total forest area required to counterbalance plant emissions (Equation 1).

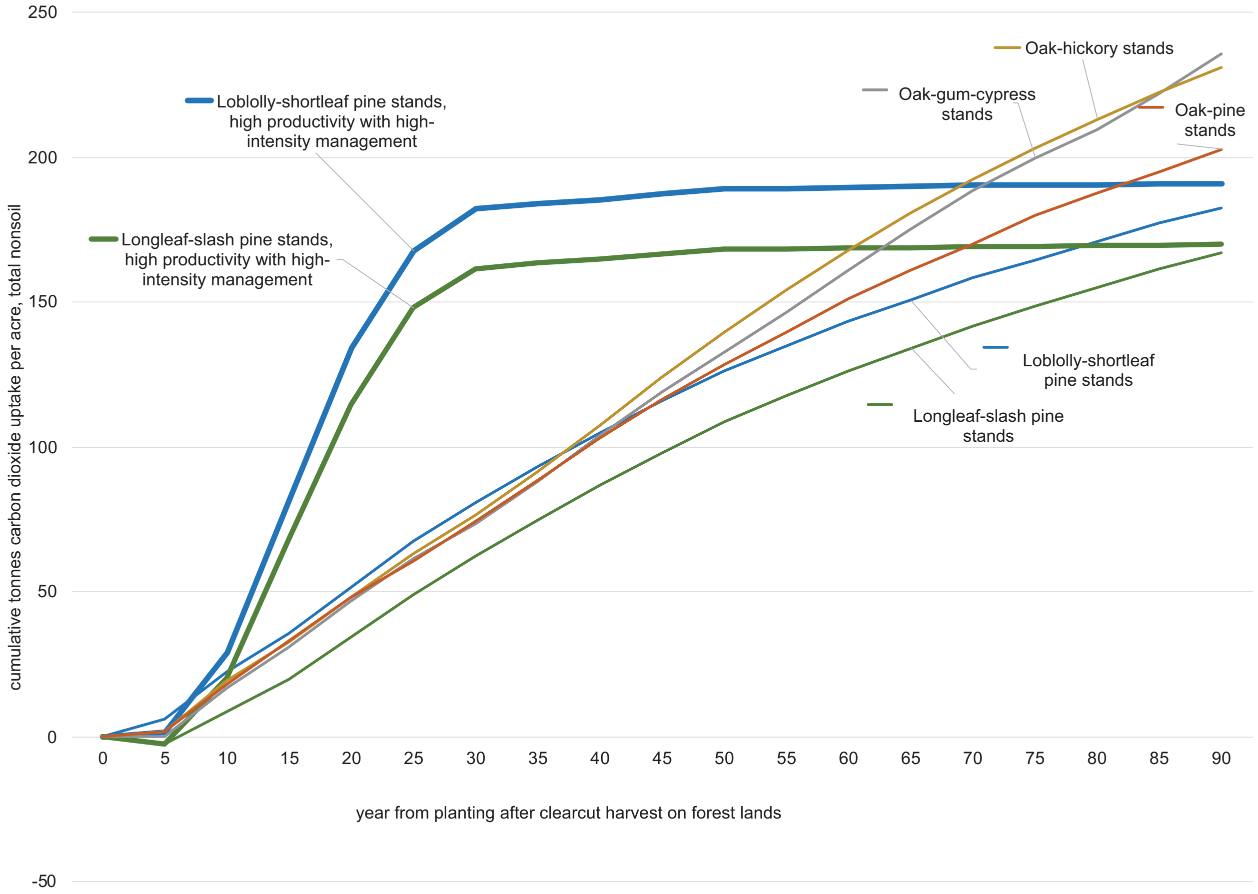

Figure 3. Growth curves for Southeastern forests, cumulative tons of carbon dioxide uptake per acre. Source: Data from [36].

LAND REQUIRED TO COMPENSATE FOR COAL PLANT EMISSIONS USING FORESTRY-BASED CDR IN GEORGIA

Trees do not mature instantaneously. As such, we must select both a specific year's emissions to be compensated via forestry CDR and a forest age to determine (1) required volume of removal and (2) cumulative removal per unit of area by that date. For this work, we select 2050 as the target year based on Southern Company's target of net-zero emissions by 2050, which is year 30 of growth assuming planting in 2021. As figure 3 shows, high-productivity, high-intensity management forests essentially reach full uptake after 30 years, while less intensively managed forests reach about 30–40% of their lifetime uptake by year 30.

Based on the assumptions in this piece, the total new area that would need to be planted in 2021 for the forestation project to remove a mass of CO_2 equal to Georgia Power's share of projected Plant Scherer's 2050 emissions by 2050 is about 15,000 –16,000 acres for high-productivity, high-intensity management forests. Note this entails dedicating 30 years of growth (and then permanent maintenance) to compensatory removal of 1 year of emissions. For less intensively managed forests, assuming the first 30 years of growth are used to compensate for emissions in 2050, this value grows to 33–42,000 acres. (Ongoing growth in these less intensively managed forests could contribute to counterbalancing additional emissions past 2050.) For context, offsetting all 2021–2050 from the entire output of Plant Scherer (rather than the single-year 2050 emissions from Georgia Power's share) with forestry-based CDR in a lowest area forestation scenario (loblolly-shortleaf pine stands, high productivity with high-intensity management [36]) would require permanently dedicating over 2 million acres of currently unforested land to netting out Scherer's emissions.

How realistic is it to rely on forestry-based CDR to offset Georgia Power's share of Plant Scherer's business-as-usual emissions to reach net zero, assuming that local forestation is prioritized? We first consider opportunities to apply net-zero forestry in the plant's host county of Monroe, Georgia, which is about 250,000 acres. Of this area, about 60% was already forested as of 2011 [38] and is thus unavailable for additional forestation. Assuming all land classified as developed open space, shrub/scrub, grassland/herbaceous, pasture/hay, and cultivated crops could be permanently converted to intensively managed forest, about 81,000 acres could be forested. That is, foresting all nonbarren lands that were not forested, water/wetlands, or occupied by low, medium, or high intensity development (i.e., homes, other buildings, roads, etc.) as of 2011 would enable about 5 years' worth of Georgia Power's share of Plant Scherer's 2019-level emissions to be considered "net zero"—with a 30-year lead time. That is, this conversion would have to take place now for Plant Scherer's 2050 emissions to be considered "net zero." Assuming forestry would need to offset Plant Scherer's entire emissions rather than only Georgia Power's share, this area could counteract only about 1 year's emissions.

Extending our definition of "local" to the entire state of Georgia (Georgia Power provides service in 155 of Georgia's 159 counties), we observe that under the same assumptions (permanently foresting all nonbarren lands that were not forested, water/wetlands, or occupied by low, medium, or high intensity development as of 2011, using high-intensity industrial silviculture techniques), a maximum of less than 14 million acres is "available." Permanently converting this amount of land under high-intensity forest management would counterbalance over 800 years of Georgia Power's share of Plant Scherer's emissions. Assuming, however, that all Georgia emitters would compete for this "local" land area, note that these 14 million acres could remove only about 50 years of Georgia's total power sector CO_2 combustion emissions (about 40% of the state's energy-related CO_2 emissions as of 2018 [23]) and would require essentially permanent elimination of Georgia's agricultural industry, grasslands, shrub lands, and developed open spaces like parks. Clearly, such a land conversion is not realistic, not least because it would likely require other land conversions elsewhere to replace the lost benefits of existing land use, particularly for agriculture. This estimate also assumes that forestation provides successful permanent sequestration at the high productivities associated with heavily managed forests, despite serious and potentially climate change-exacerbated permanence risks for forestry projects [39] and challenges associated with land quality. Given Georgia's large extant timber industry [33], lands that are not currently forested could be lower quality candidates for industrial silviculture, suggesting this illustrative calculation is optimistic about CDR potential from new forestation, even assuming no life cycle GHG emissions and total conversion of potentially available land.

CDR for Difficult-to-Decarbonize Emissions

CDR can be resource intensive, which is one driver of the argument that CDR is likely best reserved for truly difficult-to-decarbonize processes [7, 40], rather than deployed for counterbalancing emissions in the much easier-to-decarbonize electricity sector, particularly coal-fired power [15]. Optimism about the potential feasibility and effectiveness of CDR could be a major risk for emissions reductions, particularly when CDR acts as mitigation deterrence (e.g., by substituting for coal plant retirement in reduction scenarios) [17]. What kinds of resource challenges does CDR face? Land limitations for terrestrial nature-based CDR, like we demonstrate here for forestation, are a known challenge, accompanied by added resource demands for nitrogen, phosphorus, and water [41]. Without harvesting and replanting, as with bioenergy with carbon capture and sequestration strategies, the requirement that carbon stocks are maintained in perpetuity is also a major barrier both for land requirements and for permanence [37, 41].

Other CDR pathways, like DACS, are less land intensive than forestation [16] but require significant energy and material inputs. Consider that a DACS facility powered by zero-carbon energy, with electrical demand of ~370 kWh and thermal demand of 5.3 GJ per ton of CO_2 captured [42], would induce demand for zero-carbon electricity equal to an estimated 70–90% of the coal-based output whose emissions are being compensated (~40% as electricity; 30–50% as zero-carbon heat, e.g., from solar thermal, that we assume could alternatively be used to produce electricity at 20–33% efficiency)—a low estimate given that CO_2 transport and storage is not energy-neutral. That is, using DACS powered by zero-carbon energy to offset Scherer's emissions could require deployment of almost as much new energy capacity as replacing the plant's output directly, but with the additional challenges of requiring some of that energy to be thermal and needing DAC facilities that—unlike zero-carbon electricity—do not yet exist at commercial scale and do not generate revenue.

In general, CDR is also costly [16], particularly relative to available mitigation strategies in settings that are not considered very difficult to decarbonize. Nonetheless, some emissions are nearly impossible to mitigate (e.g., diffuse emissions from agriculture), and CDR is necessary for removing CO_2 that is already in the atmosphere. As such, CDR is likely to be useful, if not required, for full decarbonization [15]. These valuable, resource-intensive, and resource-limited interventions are likely better deployed to counterbalance historical or difficult-to-decarbonize emissions than to support continued business-as-usual operations of fossil fuel–based electricity that can be mitigated in other ways [17].

Environmental Justice Implications of CDR for Coal-Fired Power Plants

In addition to the extensive challenges associated with land and other resource requirements for CDR and the associated interest in deploying these technologies only where truly needed, using CDR to counterbalance CO_2 emissions from coal-fired power plants poses significant environmental and climate justice challenges, which we address only briefly here. Using CDR to offset CO_2 emissions does not reduce fenceline pollution, including conventional air pollution and coal ash generation—a specifically significant challenge for Plant Scherer [43]. Trading GHG emissions has prompted concerns about transferring air toxics and other copollutants in the past [44] because not all GHG emissions reductions strategies have the same cobenefits. Similarly, other environmental burdens like water use, land occupation, noise, and impacts associated with the supply chain (e.g., fuel extraction and transportation) continue, in addition to new burdens imposed by the CDR activities. Not closing a coal-fired power plant has some benefits as well, like preservation of jobs and tax revenue, but the relative value of eliminating copollutants versus preserving jobs for people who could theoretically gain alternative employment often favors closure [10]. Replacing coal-fired electricity with zero-carbon energy means committing to the environmental burdens of the replacement infrastructure, but modern zero-carbon energy is often lower impact than coal across most categories of interest [45].

Deploying CDR itself also has significant justice implications. Increased industrialization has the potential to create new fenceline harms, resource competition, and other challenges. The requirement that removal be permanent is particularly challenging for terrestrial storage (e.g., in standing forests), as the choice to commit land to carbon storage restricts both present and future generations' ability to alternatively manage land. Issues of sovereignty, ecosystem degradation, and permanent resource occupation are particularly acute when CDR is expected to be hosted by communities not responsible for the initial emission, particularly in the Global South. For example, the heavy demand for land associated with forestation-based CDR has led to a number of proposals for using nonlocal lands, including lands like the African savanna that have not historically been forested, that pose serious colonialist and ecosystem challenges [46, 47]. Further, the consumption of limited CDR resources to offset emissions by likely higher wealth communities could meaningfully impact Global South decarbonization pathways and costs [46, 47].

Other Considerations

This case study does not address costs, life cycle GHGs (including non-CO_2 emissions), CDR approaches other than forestation, or mitigation alternatives like fuel switching or scrubbing, all of which are highly relevant for assessing potential pathways to net zero. We also note that in practice, it is very unlikely that Georgia Power or other utilities are seriously considering CDR as a method of offsetting full, unabated power sector emissions. CDR in the power sector is more likely to be used to compensate for small residual emissions, such as those from incomplete mitigative point source CCS, very low capacity factor GHG-emitting power generation, residual non-CO_2 emissions, or other low-volume, difficult-to-address emissions comprising the last few percentage of overall emissions. Additional calculations to analyze the cost of decarbonization strategies in practice, taking into consideration both initial implementation and life cycle management costs, could help further characterize the relative roles of carbon removal and technological transition in the electricity sector. Further, there are substantial uncertainties related to the cost, environmental implications, and functionality of CDR that are unlikely to be resolved without experience from deployment. Similarly, there are substantial uncertainties about how CDR's value for electricity systems might change with increased penetration of zero-carbon electricity, demand for CO_2 as a feedstock, grid responsiveness of manufactured CDR systems, the progression of learning curves, and other dynamics [9].

CONCLUSION

Relying on CDR technologies like forestation is not an easy and low-impact route to decarbonization for the electricity sector. The land use requirement is extremely high, even with unrealistic assumptions about what lands might be available for conversion to forests for CDR, especially if the land is allocated from within the region in which the emissions are created. All CDR approaches require resources, both financial and physical (e.g., land, energy, water, materials). Considerations like reserving high-impact CDR technologies for truly difficult-to-decarbonize emissions (including legacy emissions) and environmental justice issues, including both local issues (such as not capturing cobenefits of electricity sector fuel switching, like reduction of non-GHG pollutants) and global issues (like relying on communities in other countries to provide offsets), are serious. Net-zero decarbonization goals that do not include specific commitments should be investigated for plausibility, particularly if voluntary goals are being accepted as substitutes for regulatory requirements and if CDR is presented as a key strategy ahead of clear mitigation plans.

CASE STUDY QUESTIONS

1. Does your electric utility have a decarbonization target? What about your state? If so, what is it?
2. Under what conditions do you think that forestation or other types of CDR could be viable in the electricity sector? Consider not just today's electricity sector but also one that might be nearly decarbonized.
3. In your community, where would you advocate placing CDR facilities? Is the answer different for biological approaches like forestation versus technological approaches like DACS? What kinds of concerns, reasons for support, or other reactions do you think your community might have?
4. How viable is preservation of fossil fuel–fired electricity under a zero GHG constraint? Why?
5. How do the local and global environmental justice challenges differ, especially if a fossil fuel–fired power plant stays open in one community and CDR takes place somewhere else, potentially internationally?

AUTHOR CONTRIBUTIONS

Conceptualization: KR, EG; data curation: KR, EG; investigation: KR, EG; visualization: KR, EG; writing—original draft: KR; writing—review and editing: EG; supervision: EG; validation: EG.

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COMPETING INTERESTS

The authors have declared that no competing interests exist.

DATA ACCESSIBILITY STATEMENT

All data used in this work are available through the references.

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SUPPLEMENTAL MATERIAL

Teaching Notes. Docx.

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