OCTOBER 2021
IB: 21-010-A

ISSUE BRIEF

A BAD BIOMASS BET

WHY THE LEADING APPROACH TO BIOMASS ENERGY WITH CARBON CAPTURE AND STORAGE ISN'T CARBON NEGATIVE

With every passing year—with every record-setting temperature or unthinkably destructive flood—the dangers of climate change become more apparent. As policymakers around the world increasingly recognize the devastating impacts of climate change, there is growing interest in not just curtailing new emissions of heat-trapping greenhouse gases from smokestacks, tailpipes, and buildings, but also finding ways to remove significant quantities of these gases already in the atmosphere, particularly carbon dioxide. In fact, most pathways modeled by the Intergovernmental Panel on Climate Change (IPCC) to avoid the worst impacts of climate change rely on extensive efforts to remove carbon dioxide from the atmosphere.[1]

One approach championed by the biomass industry is burning plant matter—most notably, trees and other wood from forests—as fuel to create electricity and capturing the resulting emissions from the power plant smokestack.[2] The technical name for this is "bioenergy with carbon capture and storage" (BECCS), and it is virtually the only technological carbon dioxide (CO_2) removal option explicitly included the IPCC's 2018 models.[3] BECCS is a particularly hot topic in the United Kingdom where multiple committees and agencies of the government are studying it.[4] However, despite its prominence in the IPCC report, policymakers should not assume BECCS is carbon negative. Studies have

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already shown that the widespread use of this technology would tax global ecological limits, threaten public health, and cost a fortune.[5] Furthermore, the IPCC models largely looked at scenarios in which biofuels (transportation fuels made from biomass) are supplied primarily by dedicated specialty crops, while the U.K. government is most focused on biopower (electricity made from biomass) from forests and forest residues.[6] The analysis described in this issue brief shows that this forest/wood-based approach to BECCS, as it is likely to be implemented initially, will make the impacts of climate change worse, not better.

The biomass industry wants governments to adopt the idea that BECCS is inherently carbon negative (i.e., that it will result in a net removal of CO_2 from the atmosphere). This claim is based on the erroneous premise that bioenergy on its own is carbon neutral. Forests and other plants absorb carbon; thus, the argument goes, any carbon released while burning bioenergy can be absorbed by new plants as they grow. Artificially capturing and sequestering emitted CO_2, proponents say, would allow those same plants to absorb additional carbon, making the BECCS process carbon negative. However, scientists are clear that this simplistic picture of bioenergy and BECCS is flawed. Biopower from forests without carbon capture is rarely carbon neutral.[7] According to the IPCC, it is inaccurate to "automatically consider or assume biomass used for energy [is] 'carbon neutral,' even in cases where the biomass is thought to be produced sustainably."[8] Since bioenergy is not inherently carbon neutral, BECCS is not inherently carbon negative.

Moreover, adding carbon capture and storage (CCS) to a power plant requires additional energy for installation and operation, and ultimately no CCS technology captures *all* of the CO_2 at the smokestack.[9] Neither of these sources of carbon are currently accounted for by BECCS proponents.

Finally, BECCS proponents try to focus only on the carbon emissions resulting from combustion. However, NRDC commissioned a new analysis to examine the emissions from each step in the biomass supply chain, and our model revealed that more than one third of carbon emissions occurs off-site rather than at the power station and thus cannot be captured by the addition of CCS at the smokestack. This makes it difficult for BECCS to be carbon neutral, much less carbon negative.

This issue brief disaggregates and quantifies these *uncapturable* emissions in one specific and common scenario: pellets made of wood from pine plantations in the southeastern United States fueling a BECCS operation in the United Kingdom. Our analysis shows that this approach to BECCS not only is not carbon negative but drives substantially more carbon pollution than the current electrical grid averages in either the United States or the United Kingdom.

Given this information, it is clear that policymakers should not waste money on this approach to BECCS and should look carefully before betting on BECCS more generally.

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UNCAPTURABLE CARBON EMISSIONS ALONG THE BECCS SUPPLY CHAIN

The process of burning wood to generate electricity at large scale starts long before the smokestack. Producing the fuel requires cutting down trees, transporting the trees, drying the wood, turning the wood into pellets, and transporting the pellets. Only after all that can it be burned in a power plant. However, when talking about CCS, only the emissions from the power plant can potentially be captured; emissions from making and transporting the pellets are uncapturable. In addition, because old trees store more carbon than young growth, harvesting wood leads to "forgone sequestration," the carbon storage that would have occurred over time in the uncut forest but never materializes—a loss that occurs even when accounting for regrowth of the new forest (the difference between dark and light trees in Figure 1). This loss of sequestration also cannot be captured at the smokestack.

To estimate uncaptured BECCS emissions and better understand if and under what conditions BECCS helps fight climate change and when it makes things worse, NRDC commissioned a study to model carbon emissions in one particular supply chain: Wood sourced from loblolly pine plantations in the southeastern United States used to produce pellets, which are then burned as fuel in the United Kingdom.

This scenario is representative of the most common supply chain for biomass to electricity. The largest investments in biopower without carbon capture have been made by the U.K. power company Drax, which operates the single largest power station in the United Kingdom and fuels two-thirds of it with biomass.[10] Drax sources over 60 percent of its wood from the U.S. Southeast, sourcing biomass in the form of wood pellets from Enviva, the largest manufacturer of wood pellets in the world.[11] Drax also operates three company-owned pellet mills in Louisiana and Mississippi, which it uses to self-supply biomass.

Drax is pushing the U.K. government to subsidize BECCS heavily, and the U.K. government appears poised to rely heavily on BECCS in its plan for achieving net-zero emissions by 2050 under the Paris Agreement.[12] While our analysis used data from Drax and southeastern U.S. forests, the results presented below suggest we should be looking closely and skeptically at claims of carbon negative emissions from BECCS more generally.

Using the numbers generated from our model, we found that for every megawatt-hour (MWh) of electricity that a standalone biopower plant would deliver to the grid, the uncapturable emissions along the supply chain equal 558 kilograms of carbon dioxide equivalent (kg CO_2e). The total emissions rate from a bioenergy plant without CCS is 1,481 kg CO_2e/MWh. When you add in CCS—which

FIGURE 1: SOURCES OF EMISSIONS FOR STANDALONE BIOPOWER AND BECCS

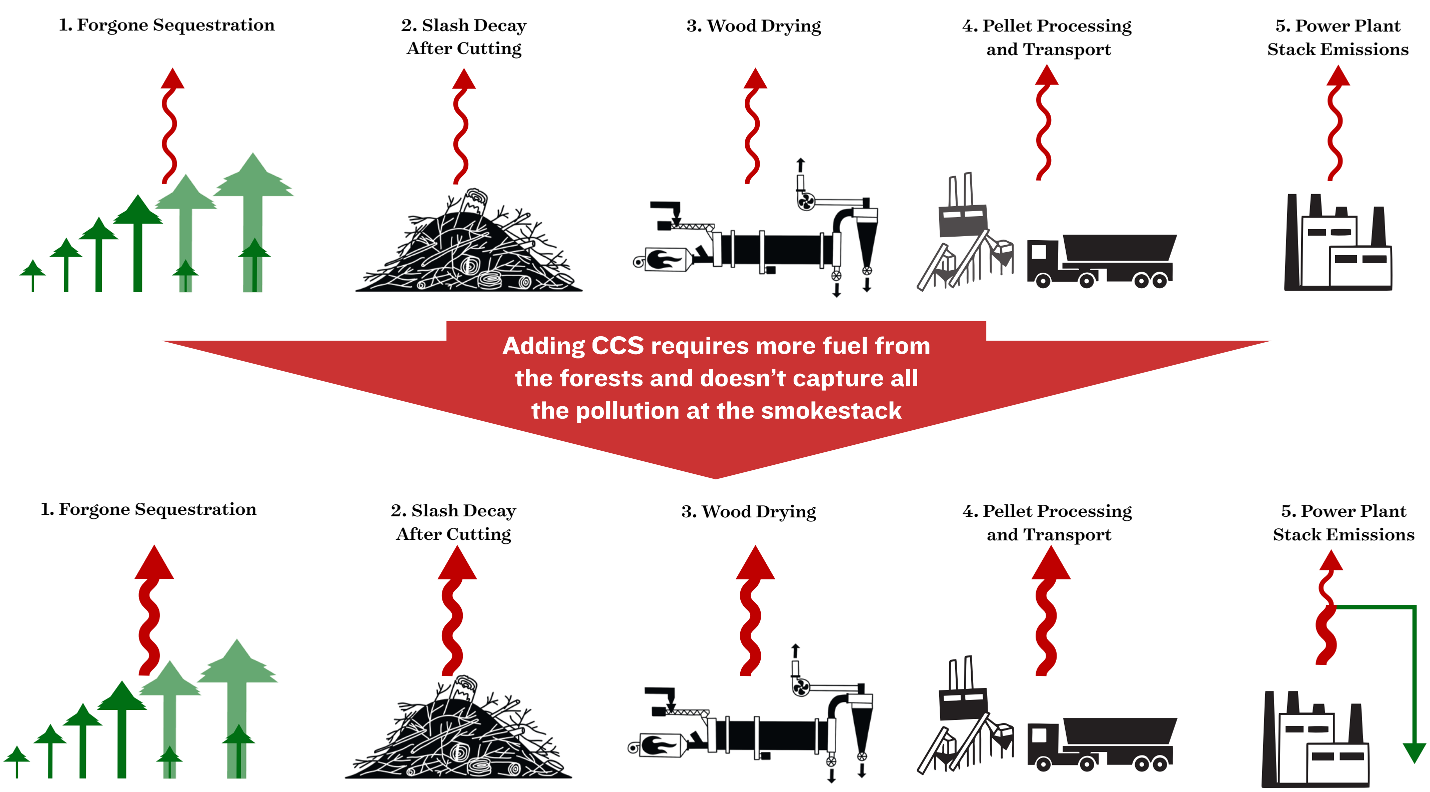
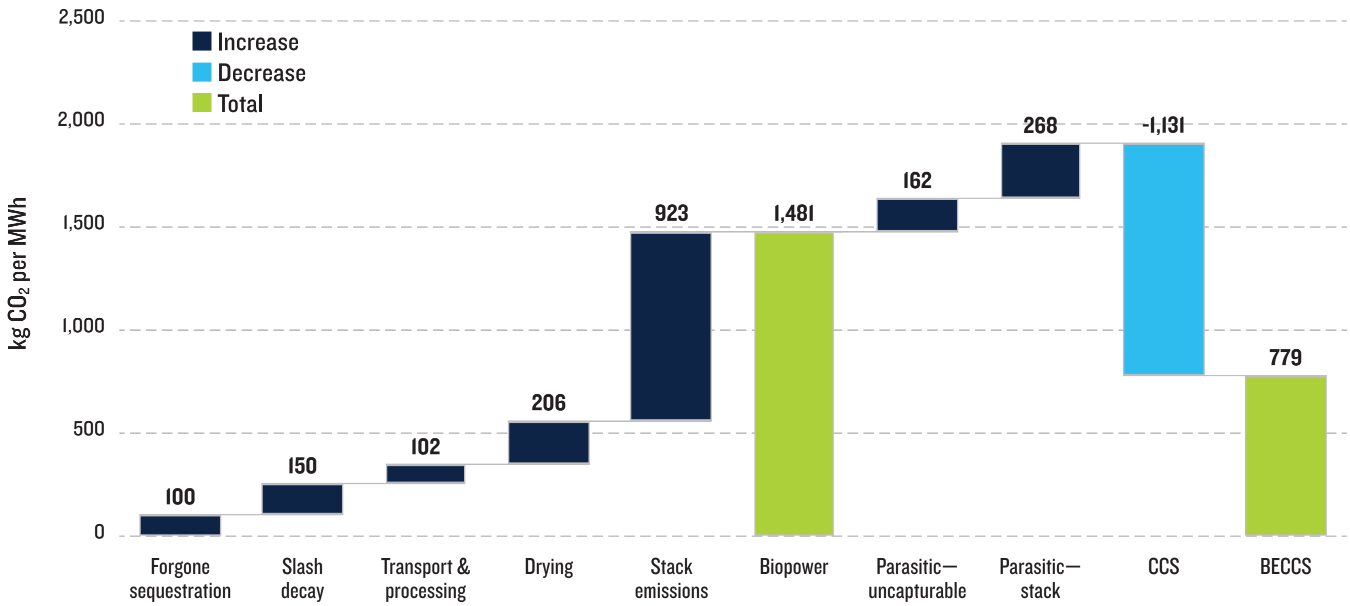


FIGURE 2: SUMMARY OF THE EMISSIONS FROM BIOPOWER AND BECCS



requires more fuel and does not have a 100 percent capture rate—the result is significant remaining emissions: 779 kg CO_2e/MWh, as shown in Figure 2 (for calculations, see the methodology section at the end of this report). This is equal to about 80 percent of what comes out of a coal plant's smokestack per megawatt-hour.

The uncaptured emissions from BECCS are equal to about 80 percent of what comes out of a coal plant's smokestack per megawatt-hour.

Bioenergy Reduces the Amount of Sequestered Carbon in a Forest—Increasing Carbon in the Atmosphere Instead

The common fallacy when talking about large-scale electricity generation from burning forest biomass is that because the trees absorbed their carbon from the atmosphere and can be replanted and grow back, over a long enough period of time cutting and burning forests won't change the balance of carbon stored on the land versus in the atmosphere.[13] Even if this were true, simply maintaining the current amount of sequestered carbon in the world's forests is not enough to avert the worst impacts of climate change. All pathways identified by the IPCC to address the climate crisis involve not just maintaining but enhancing forest carbon sinks.[14] Meanwhile, our model shows that bioenergy does not even maintain carbon sequestration levels; cutting and burning forests in the southeastern United States leads to a net shift of carbon from the land to the air that lasts for decades.

When a stand of mature trees (about 25 years old in a southeastern plantation) is cut down or thinned, new trees can regrow, but the younger stand absorbs less carbon than the mature trees for decades.[15] Forgone sequestration, as mentioned earlier, is the difference in carbon storage between newly planted saplings in a harvested forest and the older forest that would have remained uncut in the absence of bioenergy demand.[16] Forgone sequestration happens even under the best-case scenario in which trees are replanted and/or regrow immediately.

In the southeastern plantations that we modeled, this accumulation of non-sequestered carbon lasts for decades until the new stand has grown old enough to balance out the sequestration debt that the cutting has caused. This picture is a little better when forests are thinned, which is the process of removing some trees so that those remaining have less competition for sunlight and nutrients and therefore can grow faster.[17] In forest plantations, this is done to maximize the financial value of the overall harvest. Unfortunately, the result is still more than two decades of forgone sequestration in the forest.

Forgone sequestration is a significant source of emissions that carbon accounting regimes in the United Kingdom and elsewhere currently ignore.[18] It results in decades during which there is more heat-trapping carbon in the atmosphere than there would have been absent bioenergy production. The IPCC has made it clear that we must immediately, dramatically reduce our carbon emissions to avoid the worst effects of climate change. Deploying biopower plants at a global scale would do the opposite.[19]

Our model was able to quantify this forgone sequestration and found that for a southeastern loblolly pine plantation, harvesting the wood to generate 1 megawatt-hour at a standalone biopower plant leads to between 68 and 370 kg CO_2e of forgone sequestration. The lower end of the range reflects thinning practices, and the higher end represents the impact of clearcutting (where whole sections of forest are cut to the ground and then replanted). For comparison, a natural gas power plant emits about 360 kg CO_2e/MWh at its smokestack.[20]

Leftover Woody Materials Release Carbon as They Decay

After harvesting wood, there are treetops, limbs, and other woody materials left behind; these materials are known as "slash." As slash decays, it breaks down just like a compost pile. Slash returns important nutrients to the forest soils, but most of the carbon ends up back in the atmosphere. Our model found that the slash from harvesting wood to generate 1 megawatt-hour at a standalone biopower plant releases about 150 kg CO_2e.

Drying, Processing, and Transporting Pellets Takes Energy—and Emits CO_2

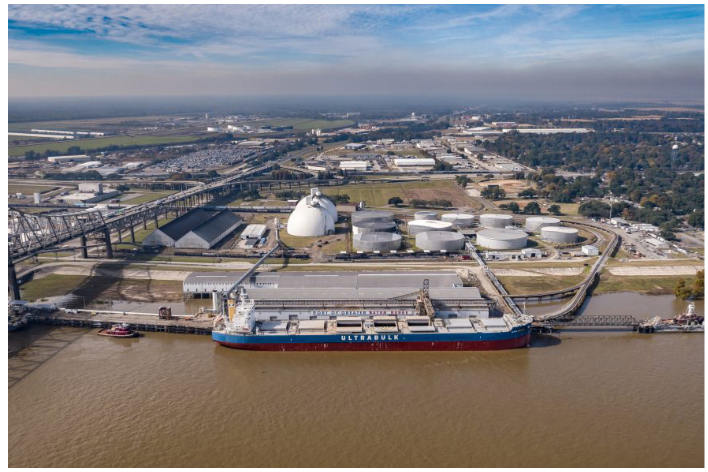
Wood must be dried before it can be processed into pellets. Just like drying your laundry, drying out this wood requires heat, and making that heat generates significant emissions. Even if the heat comes from burning some of the wood, these are emissions that can't be captured by CCS. Our model found that this step in the supply chain can generate about 206 kg CO_2e/MWh.

In addition to drying, wood needs to be transported to the processing site, ground and compressed into pellets, and then shipped, in our scenario across the Atlantic. All of these steps require the use of heavy machinery, trucks, and ships—all typically run on fossil fuels. These steps alone can generate about 102 kg CO_2e/MWh.

CCS Technology Takes Energy and Does Not Capture Everything at the Smokestack

While the focus of our model is on the uncapturable emissions associated with the bioenergy supply chain, it is important to note that carbon capture and storage technology both requires additional energy and does not have a 100 percent capture rate. Carbon capture technology is still fairly new. Current capture rates stand at around 90 percent, and the literature suggests that it will improve to only about 95 percent once the technology is mature.[21]

At the same time, capturing carbon from flue gas requires extra energy at the power plant.[22] This is especially true if capture technology is bolted on to an existing power plant (as is the case with most current plants) instead of integrated into the plant's design.[23] Our model assumes that adding CCS requires about 29 percent more energy, which is a midpoint between bolting on and integrating capture



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technology. This means burning more pellets and producing more of the uncapturable emissions discussed above. When considering the additional energy required for CCS technology, combined with the 95 percent capture rate, our study found that generating 1 megawatt-hour at a BECCS power plant leads to 779 kg CO_2e. As noted earlier, this is alarmingly close to the amount of pollution that a coal plant emits.

CONCLUSION

Our modeling shows that employing BECCS at a power station like the one operated by Drax, while relying on the biomass supply chains similar to what Drax predominantly relies on today, will make the climate crisis worse for decades to come. It is possible that burning other types of biomass would be less harmful, but this approach to BECCS isn't even close to carbon neutral, let alone carbon negative.

And there is no reason to think the situation is about to change. In fact, Drax is locking in its import supply chains. The company recently purchased Pinnacle Renewable Energy in Canada, the second-largest producer of industrial wood pellets in the world, and now has ownership interests in 17 other pellet plants and development projects across the United States and Canada.[24] This makes Drax not only the operator of the largest wood-burning power station in the world, but a top pellet manufacturer, with interests in expanding global markets for bioenergy.

What's more, this analysis doesn't take into account other challenges to BECCS. Assuming a carbon-negative approach to BECCS could be found, the amount of land that would need to be dedicated to biomass production would be enormous to meet the expansive visions some have for the technology. The integrated assessment models used by the IPCC for BECCS focus disproportionately on low-carbon energy crops and agricultural residues, they assume ambitious increases in available land and agricultural yields to furnish liquid biofuels, and many treat these feedstocks and end uses as carbon neutral.[25,26,27] Even with their underestimations, the IPCC models that include BECCS

in the pathway for limiting global warming to 1.5 degrees Celsius require up to 0.8 billion hectares of land.[28] That's equal to about 16 percent of the land currently used for agriculture worldwide; devoting that much land to biomass production risks major impacts on freshwater supplies, wildlife habitat, and food security.[29]

Furthermore, burning wood—just like burning fossil fuels—produces a host of local and regional air pollutants that cause an array of health harms, from asthma attacks to cancer to heart attacks, resulting in hospital visits and premature deaths.[30] These can be reduced through pollution controls but not eliminated.

Finally in addition to the terrifying land implications of deploying BECCS at scale and the public health threat from burning wood, there is the financial cost of BECCS. Drax is seeking tens of billions of pounds in subsidies from the U.K. government to try to make BECCS work. A recent estimate suggests that a proposed BECCS plant at the Drax power station will require a total £31.7 billion ($42.9 billion) in subsidies over 25 years.[31]

The bottom line is that policymakers around the world should not bet on BECCS. Any program to subsidize BECCS at Drax or elsewhere using supply chains similar to the one modeled here will be ineffective in drawing down emissions, risk significant harm to nature, and divert public resources that would be better invested elsewhere. Instead, policies and public dollars should be invested in proven options, such as energy efficiency, non-emitting renewables such as wind and solar, and protecting existing forests and growing more of them.

METHODOLOGY

Our analysis is intended to inform policy decisions, not to estimate emissions from specific power plants. To this end, the model we commissioned is heuristic and available to the public. While it has the capacity to look at a range of feedstocks, we have set the inputs to assess both the thinning and the clearcutting of southeastern loblolly pine plantations to generate the wood to produce pellets for electricity.

While the model looks just at the results for a BECCS power plant, we have broken out the results into those for a standalone biopower plant and then a BECCS plant.[32] This highlights the fact that uncapturable emissions are very much a concern for standalone biopower too. This methodology section lays out how we used the results from the model to calculate the emissions presented above.

Forest Emissions

To calculate forest-related emissions, we needed to decide what type of forests to model. Drax reports getting a majority of its pellets from the U.S. South; of that, roughly one-quarter comes from thinnings and 38 percent from "low-grade round wood." (Most of the remainder of the feedstocks are mill residues that don't result in any forgone sequestration.[33]) This categorization is unclear, as thinning is a harvest practice and low-grade round wood is a class of timber. The alternative to thinning in a plantation is clearcutting. To understand the policy implications of building BECCS around similar sourcing, we first assumed that both thinnings and low-grade round wood are coming from loblolly pine plantations and then looked at the two different harvest practices. For this type of southeastern forest, thinning would generate forgone sequestration equal to 68 kg CO_2e/MWh, and clearcutting would generate 370 kg CO_2e/MWh.[34] If we assume that the low-grade round wood comes from thinning, we get 63 percent of the feedstock causing thinning-level forgone sequestration, with no further forgone sequestration from the balance of feedstock. This sets a lower limit of 43 kg CO_2e/MWh of forgone sequestration. On the other hand, if we assume the low-grade round wood comes from clearcutting and weight the forgone sequestration accordingly, we get 157 kg CO_2e/MWh. We have used the midpoint, 100 kg CO_2e/MWh, as the nominal value.

The other source of forest emissions that must be accounted for is the decay of the slash—the tops and limbs left in the forest after thinning or clearcutting. These are important for a healthy, nutrient-rich soil, but some are taken to be burned to dry the wood that will be turned into pellets. Per our model, decay of the remaining slash results in 147–331 kg CO_2e/MWh for loblolly pine and is the same for thinning and for clearcutting.[35] Applying this to 63 percent of the feedstock to mirror Drax's mix, we have emissions of 93–208 kg CO_2e/MWh and a midpoint nominal value of 150 kg CO_2e/MWh.

Pellet Drying, Processing, and Transportation

To look at forest biomass fueling power plants in the United Kingdom, we need to add the emissions associated with pelletizing and transporting pellets to the outputs from our model. Estimates for transport and processing emissions range from 109 to 160 kg CO_2e/MWh.[36] Recent reporting from Drax for processing and transport estimates these emissions at 109 kg CO_2e/MWh, which includes 7 kg CO_2e/MWh of emissions resulting from energy used to dry the wood in advance of pellet production.[37] Because our model has generated a separate estimate for emissions from drying (below), we have adjusted Drax's reported value to 102 kgCO_2e/MWh to reflect transport/processing absent drying and to avoid double counting.[38]

Drying wood in advance of pellet production generates significant emissions. At harvest, a pine bole's mass can be over half water by weight.[39] This means that for every pound of oven-dry wood, green wood can hold more than a pound of water. Feedstock for a wood pellet plant, however, is limited to a moisture content of approximately 12 percent or less to manufacture finished wood pellets with a 7 percent moisture content.[40] For loblolly pine, our model, which is based on a review of the industry literature, generated estimates of pellet manufacturing drying emissions ranging from 190 to 222 kg CO_2e/MWh, and we use the midpoint, 206 kg CO_2e/MWh, as a nominal value.[41]

Carbon Capture and Storage

As explained earlier, capturing carbon from flue gas requires extra energy, known as parasitic load, and capture technology is does not capture all the CO_2.[42] Using capture technology bolted on to an existing power plant is generally assumed to require more energy than capture technology integrated into the power plant's design.[43] We use our assumptions around bolt-on CCS technology to set our high parasitic load value and estimates from the literature for integrated design to set our low value. Our consultant surveyed published literature to discover that estimates of parasitic load for both approaches ranged widely, increasing the power plant's fuel demand by 15 percent to 43 percent. Because assessing this aspect of CCS technology is not our focus here, we simply chose the midpoint of this range, 29 percent, as our nominal value. This extra energy consumption at the power plant means more forests clearcut or thinned; more forgone sequestration; more slash decay; and more pellet drying, processing, and transporting. Adding up the extra uncapturable emissions from the fuel needed to meet the parasitic load, we get 162 kg CO_2e/MWh. Furthermore, when this fuel is burned, there are more emissions at the stack—about 268 kg CO_2e/MWh.[44]

The efficiency of carbon capture technology is also a function of technological maturity. Current capture rates are around 90 percent, and the literature suggests that it will improve to about 95 percent once the technology is mature.[45] We use the more favorable assumption for CCS and use 95 percent as our nominal value for capture efficiency.

Adding Up the Emissions From BECCS

Once the forest is cut and the pellets are made and shipped across the ocean, they are burned in a power plant. The top 10 percent of coal power plants in the United States have an average efficiency of about 37.6 percent.[46] We use this efficiency to model a biopower plant without CCS. Meanwhile, all the carbon contained within the pellets is emitted from the stack. This results in a release of about 923 kg CO_2e/MWh into the atmosphere.[47] These are the stack emissions just for biopower without CCS.

If we add up the emissions for a simple biomass-fueled power plant, we have 559 kg CO_2e/MWh of uncapturable emissions plus 923 kg CO_2e/MWh at the stack for a total of 1,481 kg CO_2e/MWh. Again, these are just the emissions for biopower without CCS.

When we add emissions associated with meeting the parasitic load, we get 162 kg CO_2e/MWh extra uncapturable emissions and 268 kg CO_2e/MWh extra stack emissions. With a 95 percent capture efficiency, 1,131 kg CO_2e/MWh are stored. As is summarized in Figure 2, this leaves BECCS responsible for an increase in pollution of 779 kg CO_2e/MWh.

For reference, the stack emissions of a combined-cycle combustion turbine plant burning natural gas at 50 percent thermal efficiency are 360 kg CO_2e/MWh, and the U.S. national average grid emission rate is 430 kg CO_2e/MWh.[48] In Europe, U.K. grid emissions average 233 kg CO_2e/MWh and E.U. grid emissions average 255 kg CO_2e/MWh.[49]

ENDNOTES

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6 According to the IPCC, their integrated assessment models assume bioenergy is supplied mostly from second generation biomass feedstocks such as dedicated cellulosic crops (for example, miscanthus or poplar) as well as agricultural and forest residues, with forest residues a relatively very small component. IPCC, *Global Warming of 1.5 °C, Chapter 2*, 124, https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_Low_Res.pdf.

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13 See for example this claim from the National Alliance of Forest Owners: "Because the energy is produced using organic, renewable, regenerating material that follows a natural carbon cycle, the use of wood biomass for energy production does not increase greenhouse gas (GHG) concentrations in the atmosphere over time if done sustainably." National Alliance of Forest Owners, "Issues: A Renewable Resource," accessed September 28, 2021, https://nafoalliance.org/issues/a-renewable-resource/.

14 IPCC, *Global Warming of 1.5 °C: Summary for Policymakers*.

15 James E. Smith et al., *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States*, U.S. Department of Agriculture, General Technical Report, Forest Service, April 2006, http://www.actrees.org/files/Research/ne_gtr343.pdf.

16 It is tempting to argue that since plantations are grown for merchantable wood, they would be cut down anyway and thus there is no forgone sequestration. There are two reasons this is wrong. First, bioenergy adds marginal demand maintaining or increasing the land area managed, meaning foregone sequestration happens directly or indirectly. Second, in the context of evaluating a climate policy, the alternative should be the best use of the land, which means cutting down a forest comes with the cost of foregone sequestration.

17 This process is known as "release." Release is a forest stand's growth response to the removal of trees (in this case, thinning) that compete for nutrients and sunlight. Maryland Deptartment of Natural Resources, *Glossary of Forest Terms*, accessed September 23, 2021, https://dnr.maryland.gov/forests/Pages/gloss.aspx.

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24 "Drax Completes Acquisition of Pinnacle Renewable Energy Inc," GlobeNewswire, April 13, 2021, https://www.globenewswire.com/news-release/2021/04/13/2209296/0/en/Drax-Completes-Acquisition-of-Pinnacle-Renewable-Energy-Inc.html; "Drax Begins Construction of the First of Three New Pellet Plants in Arkansas," Lesprom, May 7, 2021,, https://www.lesprom.com/en/news/Drax_begins_construction_the_first_of_three_new_pellet_plants_in_

Arkansas_98713/.

25 According to the IPCC, their Integrated Assessment Models (IAMs) assume bioenergy is supplied mostly from second generation biomass feedstocks such as dedicated cellulosic crops (for example Miscanthus or poplar) as well as agricultural and forest residues, with forest residues a relatively very small component. IPCC, *Global Warming of 1.5 °C; Chapter 2,* pg 124.

26 In the IPCC assessments, BECCS is not limited to the power sector, with IAMs projecting on average at least 60 percent of primary energy from BECCS going to liquid biofuels. See Mathilde Fajardy et al., *BECCS Deployment: A Reality Check*, Imperial College of London, Grantham Institute, Briefing Paper No 28, January 2019, 3. https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf.

27 Almost all of the IAMs used by the IPCC assume that the feedstocks and/or end uses as carbon neutral; See, Isabela Butnar et al., "A Deep Dive Into the Modelling Assumptions for Biomass with Carbon Capture and Storage (BECCS): A Transparency Exercise," *Environmental Research Letters*, July, 2020, 7, https://iopscience.iop.org/article/10.1088/1748-9326/ab5c3e/pdf; Duncan Brack and Richard King, "Net Zero and Beyond: What Role for Bioenergy with Carbon Capture and Storage?", Chatham House, Research Paper 29, January 2020, https://www.chathamhouse.org/2020/01/net-zero-and-beyond-what-role-bioenergy-carbon-capture-and-storage-0/beccs-carbon-negative.

28 Fajardy et al., "BECCS deployment: a reality check."

29 Creutzig et al., "Considering sustainability thresholds for BECCS"; Ai et al., "Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation."

30 ALA et al., "Letter from prominent health organizations to U.S. Congress."

31 MacDonald and Harrison, "Understanding the Cost of the Drax BECCS Plant to UK Consumers."

32 Please see the supplemental materials for detailed calculations.

33 See, for example, Drax Group, *Annual Report and Accounts 2020*; Drax reports the proportion of feedstocks in its U.S. supply from "mill waste" (35 percent), "branches and tops" (2 percent), "thinnings" (25 percent) and "low grade roundwood" (38 percent).

34 Based on the tCO2e/mmBtu for 20-year foregone sequestration in Technical Appendix (Table 6) converted to an output basis assuming a heat rate of 9.08mmBtu/MWh for a stand-alone biopower plant with no CCS. See pp. 17–18 of the Technical Appendix and supplemental materials; note that this heat rate is aggressive for a solid fuel power plant.

35 See endnote 27.

36 Duncan Brack, *Woody Biomass for Power and Heat: Impacts on the Global Climate* (2017), Chatham House, https://www.chathamhouse.org/sites/default/files/publications/research/2017-02-23-woody-biomass-global-climate-brack-final2.pdf ; Mary Booth, "New UK Biomass Policy Removes Subsidies For High-Carbon Wood Pellets," Partnership for Policy Integrity, (2018); Drax Group, "Biomass Supply Chain Emissions," accessed TK, https://www.drax.com/sustainability/sustainable-bioenergy/sourcing-sustainable-biomass/.

37 Drax's estimates of supply chain emissions report 7 kg CO2/MWh. This represents only 3 percent of drying energy needs based on our estimate of 237 kg CO2/MWh. They have claimed the majority of their drying emissions are zero, based on the false assertion that these "biogenic" sources (such as logging slash) produce no emissions. See Drax Group, *Annual Report and Accounts 2020;* and Drax Group, "The Biomass Carbon Calculator," accessed September 26, 2021, https://www.drax.com/sustainability/sustainable-bioenergy/the-biomass-carbon-calculator/.

38 Note that Drax has reported this for a stand-alone biopower plant; so, we don't need to adjust for CCS.

39 U.S. Department of Agriculture, Forest Products Laboratory, *Wood Handbook: Wood as an Engineering Material*, General Technical Report FPL–GTR–190, April 2010, https://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf.

40 Jaya Shankar Tumuluru et al., "A Review of Biomass Densification Systems to Develop Uniform Feedstock Commodities for Bioenergy Application," *Biofuels, Bioproducts and Biorefining* 5, no. 6 (October 6, 2011): 683–707, https://doi.org/10.1002/bbb.324.

41 See endnote 27.

42 Hammerschlag, *Uncaptured Biogenic Emissions*, 16–18.

43 Pfaff et al., "Optimized Integration of Post-Combustion CO2 Capture Process."

44 For both the extra uncapturable emissions and the extra stack emissions, we calculate 29 percent of the stand-alone biopower plant emissions in these categories. This means we are reporting emissions on a MWh output-to-the-grid basis.

45 Hammerschlag, *Uncaptured Biogenic Emissions*, 16.

46 On a higher heating value (HHV) basis. Hammerschlag, *Uncaptured Biogenic Emissions*, 17-18.

47 Per our model (see rows 'Tables C1-C4'!110:129), loblolly pine has an emissions rate of 0.1016 tCO2e/mmBtu. Converting this to an output-to-the-grid basis at 9.08mmBtu/MWh results in emissions of 923 kg CO2e/MWh.

48 U.S. EPA, "eGRID Summary Tables 2018."

49 Department for Business, Energy & Industrial Strategy, "Conversion Factors 2020: Condensed Set", Tab: "UK Electricity" cell F24, accessed September 26, 2021, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/891105/Conversion_Factors_2020_-_Condensed_set___for_most_users_.xlsx; European Environmental Agency, "Greenhouse Gas Emission Intensity of Electricity Generation in Europe," accessed September 23, 2021, https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment-1.