Why scaling bioenergy and bioenergy with carbon capture and storage (BECCS) is impractical and would speed up global warming

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EXECUTIVE SUMMARY

Bioenergy with carbon capture and storage (BECCS) has generated great interest as global emissions have soared to 50 billion tons (Gt) a year of CO_2 equivalent. In theory, biomass could remove CO_2 out of the air as it grows, and a CCS system on the bioenergy power plant could permanently bury the CO_2, making BECCS potentially a "negative" emissions technology.

But **a growing body of research casts doubt on whether either bioenergy or BECCS are scalable climate solutions—or solutions at all.** Those doubts are reinforced by findings from the first dynamic, integrated global modeling of BECCS by the researchers of Climate Interactive:

1. **Policies to scale up bioenergy and BECCS would *increase* global warming for several decades, with net cooling not occurring until 2100 or beyond.**
2. **Scaling up BECCS to 2 to 3 Gt CO_2/year would require a land area the size of India.**
3. **The best bioenergy strategy right now would be to let bioenergy plants retire without replacement, rather than putting CCS systems on them.**

So, treating bioenergy as inherently zero-CO_2 or carbon neutral will invariably lead to policies harming the climate as it does in Europe—where wood is "likely to remain the biomass fuel of choice for electricity generation and heat, at least for the next 10 years and probably longer," as a UK think tank noted in 2018. **Scaling up BECCS is not carbon removal, but much more like deforestation.**

The world's top mitigation experts of the Intergovernmental Panel on Climate Change (IPCC) scaled back BECCS projections in their 2900-page report assessing scientific knowledge on mitigation in 2022. They reported, "**BECCS is not projected to be widely implemented for several decades.**" The International Energy Agency has also steadily scaled back its use from "almost 5 Gt CO_2" removal by 2060 in 2017 to only 1 Gt CO_2 removal a year by 2050 in its September 2023 1.5°C (2.7°F) scenario.

A 2022 review by the European Academies' Science Advisory Council (EASAC) of the latest evidence on BECCS "finds that **there are substantial risks of it failing to achieve net removals at all**, **or that any removals are delayed**" beyond a useful timeframe. Because of this delay in net removals, analyzing BECCS requires a dynamic model that can look over decades.

In 2021, a dynamic forest-level analysis found that after 20 years of operation, "**the uncaptured emissions from BECCS" are nearly equal to that of a coal plant.** BECCS has high emissions whether

you are clear cutting or just thinning a forest. So, scaling it up would increase net U.S. emissions for decades. Why? It would take that long for the replanted seedlings to grow and absorb enough CO_2 to make total BECCS life-cycle emissions negative compared to leaving the original trees alone and deploying the best low-carbon alternatives at that time.

As the IPCC wrote in 2022, "In the case of BECCS, it should be noted that bio-energy typically is associated with early-on positive CO_2 emissions and net-negative effects are only achieved in time (carbon debt), and its potential is limited." And this carbon debt doesn't even start to decline until biomass harvesting stops scaling up. Net negative would occur post-2100 if at all. And that means **when scaling up, the effective cost per ton of net CO_2 removed by BECCS is incalculably high because no net CO_2 is removed.**

But seriously scaling up BECCS would likely require a billion acres or more. And "**without a social justice lens, any attempt to fulfil the many land-based climate pledges is likely to perpetuate injustices**" against indigenous people and local communities, a 2020 report found. Yet, as the EASAC noted, "**the area of land required to generate energy from biomass is 50–100 times larger than for solar and wind** and thus land usage for bioenergy is inefficient."

In 2021, the UN reported "agricultural systems [are] breaking down." So, "**there is little room for expanding the area of productive land, yet more than 95 percent of food is grown on land**." The impacts of large-scale BECCS (and worsening climate change) could sharply increase food prices. A multi-year study by the World Bank, UN, and others on how to feed the world in 2050 concluded that "the proportion of plant material diverted from food and fiber to energy would be unacceptably high—and that **hopes of climate benefits are misplaced. We recommend phasing out bioenergy targets**."

Finally, if the belief in BECCS leads the world to underinvest in real solutions like renewables now, then a 2020 study finds **we risk overshooting our temperature target by "up to 1.4°C" (2.5°F)—**and thus risk crossing dangerous climatic tipping points.

The U.S. is headed toward misspending billions of dollars on Inflation Reduction Act tax credits for BECCS. **Tax credits for continuing to scale up corn ethanol are an especially bad idea. Rather than being carbon neutral (even with CCS) corn ethanol is carbon intensive and should be phased out as we shift to electric vehicles running on renewables.** Since BECCS is unlikely to be a scalable climate solution by 2050 if ever, the priority climate action this decade and next is to spend trillions of dollars deploying proven zero-carbon technologies, like solar, wind, and energy efficiency, while developing the next generation of zero-carbon technologies.

INTRODUCTION

In the past two decades, the science has grown stronger that the world needs to hold total warming to "well below 2°C above pre-industrial levels" while "pursuing efforts to limit the temperature increase to 1.5°C," as the nations of the world agreed unanimously in the 2015 Paris Agreement and reaffirmed in Glasgow in 2021. As the IPCC explained in its 2018 *Special Report on Global Warming of 1.5°C*, meeting the 1.5°C limit requires net zero global emissions by 2050, whereby whatever emissions the world can't mitigate by then would be offset by negative emissions technologies also known as carbon dioxide removal (CDR).[1]

Yet since 2000, global emissions have risen steadily to 50 Gt CO_2eq. In fact, **we are currently headed to 3°C warming or more by 2100 based on policies actually in place globally**.[2] So, many climate modelers started to consider large amounts of negative emissions in their mitigation pathways. As recently as the IPCC's 2018 *Special Report*, one of its "four illustrative model pathways" limiting warming to 1.5°C had CO_2 removal of 20 Gt/yr from 2060 on (almost entirely from BECCS).[3] In the major 2017 climate stabilization Beyond 2° scenario of the International Energy Agency, "BECCS delivers almost 5 Gt of negative CO_2 emissions in 2060."[4]

The full BECCS process has four parts (see figure):

1. Large amounts of biomass are harvested or recovered—and then transported to a bioenergy with CCS facility;
2. The BECCS facility then either burns the biomass or converts it to a fuel, separating out and capturing the CO_2;
3. The CO_2 is compressed to more than 1,000 pounds per square inch to transport it, typically via pipeline, to the storage site; and
4. The CO_2 is then injected underground—either to extract more oil (enhanced oil recovery) or simply to be stored in a non-production reservoir—and regularly monitored to verify the ongoing integrity of the storage system.

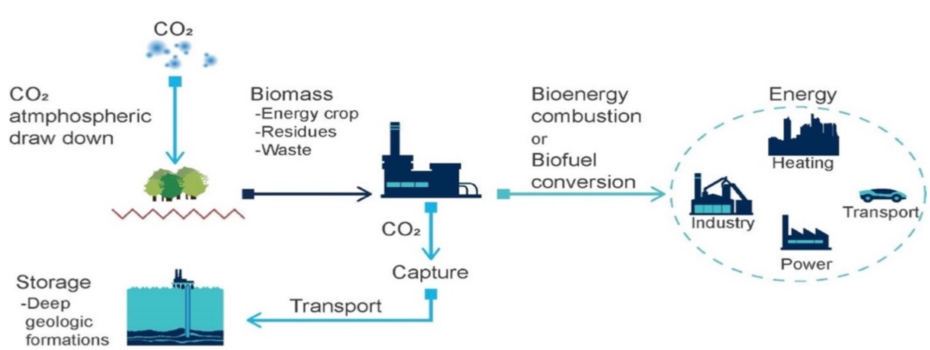

Figure: BECCS schematic *CREDIT: Global CCS Institute, 2019.*[5]

Biomass is organic material, typically from trees, food crops (like corn), dedicated energy crops (like switchgrass), or agricultural/forest/mill waste. Other forms of biomass have similar emissions as wood, but **wood, usually in pellet form, is the biomass of choice in places where biomass power is growing rapidly like the European Union**.

The fact that we are increasingly burning trees is central to understanding why scaling up biopower and BECCS would speed up global warming this century. That's because burning trees for BECCS "is associated with early-on positive CO_2 emissions and net-negative effects are only achieved in time (carbon debt)," as the IPCC wrote in 2022.[6] The carbon debt for biomass power is the total life-cycle emissions—from harvesting, drying, transporting, and burning the biomass—plus the "foregone carbon removal," which is the loss of the future CO_2 that would have been captured if you hadn't cut the trees down. "If the forest had not been cut, it would have continued to grow, removing additional carbon from the atmosphere," explains a 2022 study.[7] The emissions released plus the forgone carbon removal is the "carbon debt."

Adding CCS to the biopower plant reduces the emissions from burning the biomass but does not capture 100% of smokestack emissions and in the real-world carbon capture systems have often been far less than 90% effective. Also, the CCS system consumes a great deal of energy whose emissions must also be accounted for in any life-cycle analysis.

So, it can take decades for the replanted seedlings to grow and absorb enough CO_2 to pay off this debt and make total BECCS life-cycle emissions negative compared to just leaving the original trees alone and deploying the best low-carbon alternatives to BECCS at that time. Also, each year that more trees are harvested for bioenergy, the carbon debt just keeps rising. The debt doesn't start getting paid off until the scaling up stops. And, every year, the technology that bioenergy/BECCS is competing against and displacing has lower and lower emissions (as discussed in a later section).

Let's examine the reality that we are increasingly burning trees and then explore the issues of carbon debt and what power sources new bioenergy/BECCS plants will be displacing.

WE ARE INCREASINGLY BURNING TREES FOR BIOPOWER

The primary input for biopower in places seeing rapid growth is wood—not dedicated energy crops like switchgrass and not agricultural or forestry residues. The *New York Times*, in its 2022 article, "Europe Is Sacrificing Its Ancient Forests for Energy," reported that "wood is now Europe's largest renewable energy source, far ahead of wind and solar."[8] The problem with energy crops is they "tend to be less energy-dense and more expensive to collect and transport than wood," notes a 2018 report from the UK think tank Chatham House on "woody biomass for power and heat" in Europe.[9] So "**wood is therefore likely to remain the biomass fuel of choice for electricity generation and heat, at least for the next 10 years and probably longer**."

A 2018 study on "residues burned for bioenergy" notes that "treatment of bioenergy as 'low carbon' or carbon neutral often assumes fuels are agricultural or forestry residues."[10] While burning wood residues is far from carbon neutral,[11] "calculating net emissions from wood pellets as if feedstocks are derived from forest residues underestimates emissions because **a large proportion of pellets are made from trees, not residues**."

A 2017 Chatham House report makes a similar point.[12] "Many of the models used to predict the impacts of biomass use assume that mill and forest residues are the main feedstock used for energy, and biomass pellet and energy companies tend to claim the same," noted the report. "**Evidence suggests, however, that various types of roundwood are generally the main source of feedstock for large industrial pellet facilities. Forest residues are often unsuitable for use because of their high ash, dirt and alkali salt content**."[13]

A 2018 *Nature Communications* study concludes, "**Contrary to repeated claims, almost 90% of these wood pellets come from the main stems of trees, mostly of pulpwood quality, or from sawdust otherwise used for wood products.**"[14] The 2022 *New York Times* article noted "E.U. official research could not identify the source of 120 million metric tons of wood used across the continent last year—a gap bigger than the size of Finland's entire timber industry. Researchers say most of that probably was burned for heating and electricity."[15] **Forests in Finland and Estonia "once seen as key assets for reducing carbon from the air, are now the source of so much logging that government scientists consider them carbon emitters."**

A 2019 review article noted, "The EU's own analyses[16] found that the amounts of residues available are insufficient (or already used in the forestry supply chain) to support the increased demand from large pellet plants, and that stemwood from trees was the dominant source of biomass for US pellet plants."[17] A 350-page European Commission (EC) report explained back in 2016 that "**logging residuals (tops and limbs) are generally poorly suited for industrial wood pellets, and its share of total feedstock volume is insignificant**.[18] The report concludes "**Therefore, it is reasonable to assume**

that the increased demand for industrial pellets requires a roughly equivalent increase in logging removals in the region."

A 2021 "Letter Regarding Use of Forests for Bioenergy," to the heads of the U.S., EU, Japan, and South Korea by 500 scientists led by Peter Raven, former President of the American Association for Advancement of Science, explained, that "in recent years there has been a misguided move to cut down whole trees or to divert large portions of stem wood for bioenergy, releasing carbon that would otherwise stay locked up in forests."[19]

A 2022 review finds that "despite industry claims to the contrary, wood pellets burned by Drax and others come from wood taken from native hardwood forests."[20] They document "vast quantities of whole trees and other large-diameter wood logged via clearcutting, which is the most destructive of all logging practices." Similarly, "The Green Energy Scandal Exposed," a 2022 investigative BBC documentary "reveals how Drax is chopping down trees and taking logs from some of the world's most precious forests."[21]

THE PROBLEM WITH BURNING TREES FOR BIOPOWER: CARBON DEBT AND LONG PAYBACK

Like deforestation, cutting down trees and burning them for power releases significant emissions. And like deforestation, it also results in large foregone carbon removal—if you hadn't cut the trees down, they would have kept growing and capturing more CO_2. As noted, the emissions released plus the forgone carbon removal is the "carbon debt."

As the 2021 forest bioenergy letter by 500 scientists makes clear, the debt is significant: "**When wood is harvested and burned, much—and often more than half—of the live wood in trees harvested is typically lost in harvesting and processing before it can supply energy, adding carbon to the atmosphere without replacing fossil fuels."** Another reason the debt is big, and the payback is long is that "Burning wood is also carbon-inefficient, so the wood burned for energy emits more carbon up smokestacks than using fossil fuels. Overall, **for each kilowatt hour of heat or electricity produced, using wood initially is likely to add two to three times as much carbon to the air as using fossil fuels**."[22]

As the letter puts it, "The result of this additional wood harvest is a large initial increase in carbon emissions, creating a 'carbon debt'." The carbon debt is reduced or paid back over time if an equivalent number of new seedlings are replanted to replace the harvested trees and successfully grow to maturity. "Regrowing trees and displacement of fossil fuels may eventually pay off this carbon debt, but regrowth takes time the world does not have to solve climate change," the letter explains. "**As numerous studies have shown, this burning of wood will increase warming for decades to centuries**. That is true even when the wood replaces coal, oil or natural gas." In its 2019 report on negative emissions technologies, the National Academy of Sciences similarly notes that "harvesting live trees … may take decades or centuries to recover their original biomass and reach carbon sequestration parity."[23]

The payback time is the fastest if the new biomass plant displaces a coal plant. But very few countries in the world besides China and India are building many new coal plants. In the United States and a great many other countries, the plant that would be displaced—the next power plant that was going to be built instead—is a mixture of natural gas and renewables (see next section). And as the electric grid increasingly decarbonizes over the next decade, biopower will increasingly be displacing zero or very-low carbon technologies so this type of debt reduction will shrink toward zero—and so the payback time will increase beyond a century.

Because of the carbon debt, a biomass power plant with CCS does not start out as a net remover of CO_2. The IPCC explained in its big 2022 mitigation report that for BECCS, "bio-energy typically is associated with early-on positive CO_2 emissions and net-negative effects are only achieved in time (carbon debt), and its potential is limited."

How long it takes for a BECCS plant to shift from being a net emitter to being net negative can be determined only by a dynamic analysis of the BECCS lifecycle over decades. In particular, because so much of the original biomass carbon is not captured, the "net" emissions removed from the atmosphere by BECCS can be substantially less than the "gross" emissions captured at the smokestack. One 2013 analysis looked at the life cycle "carbon losses" from BECCS using switchgrass, an energy crop.[24] It concluded that for every 1 ton of CO_2 that gets sequestered, emissions leakage in the entire supply chain is 1.11 tons.

Putting the CCS system on a bioenergy plant by itself will result in major losses, as noted earlier. The post-combustion carbon capture and compression system requires much more power to run compared to power plants without CCS. This extra power is called the *energy penalty* or *parasitic load*. It is estimated to be 20% to 30% of a power plant's capacity.[25]

The 2021 Chatham House report notes that R&D trials at a British plant owned by a company "pioneering post-combustion BECCS technologies," imply that "the overall efficiency of the BECCS-to-power facility could fall from 36.2 per cent to 20.9 per cent, relative to the same plant without CCS."[26] As a result, "**we seem to be heading towards inefficient facilities relative to that assumed within the IAMs**" (the integrated assessment models used by the IPCC and others to examine the strategies needed to limit global warming). Four IAMs examined in one study assume efficiencies of between 31.3% and 38.8% by 2030. If IAMs have greatly overestimated the net efficiency with which the biopower plants burn biomass, then they have greatly underestimated the amount of biomass—and land, water, energy, and fertilizer—needed for a given amount of emissions reduction.

Also, the report notes that facility-level CO_2 "capture rates are often cited as being 90 per cent or more by BECCS developers, within the IAMs, academic literature and within policy briefings." But according to a 2022 analysis of 13 real world flagship CCS projects—representing 55% of CO_2 capture capacity worldwide—actual capture rates are often below 70% and "Failed/underperforming projects considerably outnumbered successful experiences."[27] Significantly, there is usually a trade-off between the capture rate and the efficiency of a BECCS power plant. As the capture rate rises, the BECCS system must draw more and more power from the plant. Higher capture rate means greater energy penalty, which means lower overall efficiency for the system.

SCALING UP BECCS WORSENS WARMING PAST 2100

Perhaps the most important finding in both the literature and the new Climate Interactive modeling results presented here occurs when analyzing an effort to scale up biopower and BECCS over decades—which is the most likely scenario if they are going to become a major climate solution. In that situation, as the scientists' letter notes, the carbon debt "increases over time as more trees are harvested for continuing bioenergy use."

A 2018 "Dynamic lifecycle analysis of wood bioenergy," explains that **"Growth in wood supply causes steady growth in atmospheric CO_2 because more CO_2 is added to the atmosphere every year in initial carbon debt than is paid back by regrowth, worsening global warming and climate change"**[28] The total carbon debt does not start getting repaid until biomass harvesting stops scaling up. The study was led by John Sterman, Director of the System Dynamics Group at MIT's Sloan School who also helps lead the work at Climate Interactive. **The study found that "growth in the wood pellet industry to displace coal aggravates global warming at least through the end of this century, even if the industry stops growing by 2050**."

So, although bioenergy from wood "can lower long-run CO_2 concentrations compared to fossil fuels," the paper concludes, "its first impact is an increase in CO_2, worsening global warming over the critical period through 2100 even if the wood offsets coal, the most carbon-intensive fossil fuel." In reality, the wood will be offsetting a far lower level of emissions that will decline over time (see next section).

Moreover, "**the carbon debt incurred when wood displaces coal may never be repaid**," notes the Sterman study "if development, unplanned logging, erosion or increases in extreme temperatures, fire, and disease (all worsened by global warming) limit regrowth or accelerate the flux of carbon from soils to the atmosphere."

In 2021, one of the only dynamic forest-level analyses looked at a typical supply chain—pinewood from the U.S. southeast used to make pellets burned as fuel in the UK.[29] It found that after 20 years, "the uncaptured emissions from BECCS are equal to about 80 percent of what comes out of a coal plant's smokestack per megawatt-hour."[30] BECCS has high emissions whether you are clear cutting or just thinning a forest. The problem is that 20 years from now, we can't be generating electricity that is only slightly cleaner than coal if we want to have any chance of meeting the Paris agreement temperature targets and avoid catastrophic climate change. We need to be generating electricity that is essentially carbon free.

The modelers at Climate Interactive took dynamic analysis to a global level using En-ROADS, which is "a global climate simulator that allows users to explore the impact that dozens of policies"—such as subsidizing CCS, pricing carbon, and improving agricultural practices—have on dozens and dozens of factors like global temperature, carbon stored in forests, land usage, and CO_2 emissions.[31]

This new modeling assumes BECCS proves to be both technically scalable, which has not been demonstrated yet, and commercially viable, for which the support of capital, citizens, and politicians remains untested. En-ROADS is a dynamic analysis (over decades) of the net system-wide CO_2 emissions removed from (or added to) the atmosphere, rather than a static snapshot of the gross CO_2 emissions captured from the smokestack. It is integrated and global so it can examine key trade-offs such as using land for bioenergy versus land for food. Incorporating these tradeoffs is essential because any model of BECCS that effectively assumes we have a nearly limitless amount of land to devote to bioenergy is simply unrealistic, as discussed in the second half of this paper.

Using En-ROADS, Climate Interactive found that policies that boost biomass power and BECCS would increase global temperatures for decades, with net cooling not occurring until the

end of the century, even under optimistic assumptions.[32] **As bioenergy or BECCS is scaled higher, the temperature rise is also higher and lasts longer, well past 2100.**

These findings are consistent with the recent scientific literature. Consider a 2022 review by the European Academies' Science Advisory Council (EASAC) —the "collective voice of European science"— of the latest evidence on BECCS. It "finds that **there are substantial risks of it failing to achieve net removals at all, or that any removals are delayed beyond the critical period** during which the world is seeking to meet Paris Agreement targets to limit warming to 1.5–2°C."[33] The EASAC review concludes "**any BECCS projects should be of limited scale, all feedstocks provided locally with very low supply chain emissions, and feedstock payback times should be very short**." Such rules would eliminate virtually all current and planned bioenergy plants.

The IPCC itself scaled back BECCS projections in its 2022 mitigation report, noting, "BECCS is not projected to be widely implemented for several decades."[34] The International Energy Agency has also steadily scaled back its use in a 2017 scenario from "almost 5 Gt of negative CO2 emissions in 2060"[35] to only 1 $GtCO_2$ (2% of total global greenhouse gas emissions) removal a year by 2050 in its September 2023 1.5°C scenario.[36]

WHAT'S THE RIGHT ALTERNATIVE TO COMPARE WITH BECCS?

"The choice of the reference system to which the bioenergy system is compared is critical since the estimated benefits of bioenergy can differ widely depending on the assumed energy system replaced." So explains the 2011 report *Using a Life Cycle Assessment Approach to Estimate the Net Greenhouse Gas Emissions of Bioenergy* by IEA Bioenergy—a collaboration among two dozen of the world's biggest emitters founded by the International Energy Agency.[37]

Similarly, "In comparative LCA studies the choice of the reference system to which the bioenergy emissions are compared is fundamental," explains a 2014 "critical literature review" on "Carbon accounting of forest bioenergy," by the EC's Joint Research Centre (JRC).[38]

IEA Bioenergy notes, "**It would be misleading to calculate the GHG emissions caused by the bioenergy system and compare these to GHG emissions for an unrealistic fossil energy system**." And yet most biopower LCAs compare it to coal—even decades into the future, which is unrealistic as both the JRC and IEA Bioenergy reports make clear. The latter explains, "**Ideally, in the most realistic evaluation, the bioenergy system should be evaluated against the energy system most likely to be displaced**."

IEA Bioenergy was suggesting natural gas level emissions (or lower) as a reasonable comparison for biopower back in 2011.[39] Today, the biggest source of new generation is zero-carbon, and the second biggest is natural gas. Few besides China and India are building a lot of new coal. So, the best reference comparison for biopower now is an emissions rate well below natural gas.[40] By 2030, the best reference plant for biopower should be at least coal or gas plant *with CCS*.[41] For an LCA of BECCS scaling up post-2035, the displaced plants should be zero carbon.

The JRC review makes this key point explicitly—you need a dynamic LCA analysis, not a static one. "In the case of a long-term analysis (several decades or centuries)," the authors note, "the changes in the reference fossil scenario have to be accounted for." And yet, "**in practically all of the studies analyzed the reference fossil system (coal or NG) is kept constant and unchanged for the whole duration of the analysis (even centuries)**." This is the case even though EU policy is to decarbonize by 2050, "implying that future savings might be much smaller than current ones," and "**it may happen that the payback time is never reached**." For a comparative LCA done correctly and dynamically, biopower might never achieve carbon neutrality.

Also, IEA Bioenergy notes "seldom have LCA studies included the emissions from indirect land use change," and in particular, "a variable that many biofuel LCA studies neglect entirely is the change in soil organic carbon (SOC) due to change in land use or land management" (discussed below).

OTHER SCALABILITY CHALLENGES FOR BECCS

Beyond the multi-decade increase in CO_2 emissions and warming it causes, trying to scale up BECCS faces several other challenges identified in the literature. The first is whether CCS is by itself going to be a commercially practical and scalable technology by 2050. As the IPCC's 2022 mitigation report *Summary for Policymakers* stated, "Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers."[42] This finding was signed off on by all the nations of the world.

A key aspect of this issue is whether the pipeline and other infrastructure for CCS is scalable. Sequestering just 3 $GtCO_2$ a year—6% of total global greenhouse gas emissions—would require infrastructure whose throughput volume of compressed CO_2 would be higher than the volume of oil extracted and transported by the global oil industry, which took a century to develop. As one expert put it, "Needless to say, such a technical feat could not be accomplished within a single generation."[43]

JP Morgan noted in its *2021 Annual Energy Paper*, "just to sequester an amount equal to 15% of current US GHG emissions, would require infrastructure whose throughput volume would be higher than the volume of oil flowing through US distribution and refining pipelines, a system which has taken over 100 years to build."[44] Yet compared to the last 100 years, we are now in a political climate where it is increasingly difficult to build even a single new pipeline. Major oil and gas pipelines have been delayed, driving up costs, or canceled outright, as **the *New York Times* reported in a 2020 article headlined "Is This the End of New Pipelines?"**[45] And those battles have already spread to CO_2 pipelines, as **the *Wall Street Journal* detailed in a September 2023 article, "A New Nimbyism Blocks Carbon Pipelines."**[46] *Greenwire* reported on October 20, 2023 that "the developer planning a 1,300-mile network of carbon dioxide pipelines through the farm belt said Friday that it's scrapping the project."[47] The company cited the "unpredictable nature of the regulatory and government processes" in two out of the five states the pipeline had to cross.

A 2020 Princeton University analysis of net-zero-by-2050 scenarios found that just to capture and store nearly one $GtCO_2$ a year, the U.S. alone might need to build over 60,000 miles of new pipelines.[48] Is this really a scalable option, especially for a technology that is not even commercial today? BECCS must compete against every other type of CCS—for coal and gas plants, for industrial facilities, and for direct air capture (DACCS)—for access to pipelines and underground storage sites.

Moreover, biopower plants are not the best use of CCS Technology. A 2015 National Academy of Sciences report concluded that, **for BECCS, "in the most common situation, there is lower net reduction in GHG emissions relative to using the same CCS capacity with fossil fuel–generated energy."**[49] Also, putting CCS on a fossil fuel plant is less expensive and more straightforward than putting it on various biopower plants. In a 2016 review, the U.S. Energy Department explained, **"Biomass is very heterogeneous in physical and chemical properties that arise from differences in genetics, degree of crop maturity, geographical location, climatic events, and harvest methods. This variability presents significant cost and performance risks and is a barrier to cost-effective bioenergy and biopower systems."**[50]

The 2022 EASAC review concluded "In view of the leakage of greenhouse gas in the production, treatment and extended transport supply chains of existing large power stations, **the science does not support the conversion of existing large-scale forest biomass power stations to BECCS**."

Thus, for the foreseeable future, if CCS does prove to be commercially scalable, it makes more sense to put such systems on existing coal and gas plants than it does to put them on biomass power stations—especially since CCS and pipeline infrastructure are, as noted, far from an unlimited resource. And unlike BECCS, fossil CCS will not consume vast amounts of land needed to sustain 10 billion people mid-century in a world ravaged by climate change.

If the goal is reducing global warming this century, then Climate Interactive's modeling indicates the optimum bioenergy strategy today is to let biomass power plants retire without replacement, rather than putting CCS systems on them. This actually reduces emissions because biomass power plants are not carbon neutral. They emit significant emissions. Also, if you simply slow down tree-harvesting for energy, you get a direct CO_2 benefit for a period of time just as you get a direct CO_2 cost when you speed up tree cutting.

BIOENERGY AND FOOD INCREASINGLY COMPETE FOR LAND

Even if BECCS did generate significant net carbon removal, it faces a tremendous obstacle to scalability because of the amount of land (and energy and water and fertilizer) required, even as the world faces "looming global land scarcity."[51] A study in *Energy Policy* on the land requirements of bioenergy notes that "land use changes necessary to supply current biomass harvests … have contributed around one third of the world's cumulative CO_2 emissions since 1750."[52] Using satellite data, a landmark 2022 study in *Nature Food* found global cropland expansion has accelerated this century, adding 250 million acres since 2000.[53]

Because of the projected increase in food demand, "the vast majority of models estimate expansion of agricultural land by 2050, including several by more than half a billion hectares" (over a billion acres). The 2022 *Land Gap Report* added up all the national climate pledges and found more than 1.5 billion acres of reforestation is required "to achieve the projected carbon removal, with the potential to displace food production including sustainable livelihoods for many smallholder farmers."[54] That means food production and reforestation could in total require more land than the contiguous US.

At the same time, "**climate change clearly poses a threat to global food production in the medium to long term**," the EC's Joint Research Centre wrote in 2020.[55] I wrote a 2011 *Nature* article on "dust-bowlification and its potentially devastating impact on food security," that explained why **feeding the world "by mid-century in the face of a rapidly worsening climate may well be the greatest challenge the human race has ever faced."**[56] Wildfires, sea level rise and salt-water intrusion, rising temperatures, extreme weather, and megadroughts threaten existing crops and farm land—and are projected to generate tens of millions of climate refugees in the coming decades, who will all need new land to live on.

So how much new land will there be left for new large-scale biomass production in the future? Not much. A 2021 synthesis report by the UN Food and Agriculture Organization (FAO) concludes that "Land and water systems are at breaking point," and "agricultural systems [are] breaking down."[57] As a result, "**There is little room for expanding the area of productive land, yet more than 95 percent of food is grown on land**."

The 2022 IPCC mitigation report explains that "Large-scale BECCS may push planetary boundaries for freshwater use, exacerbate land-system change," and push vital elements of the global ecosystem into an unsustainable range.

The U.S. National Academies 2019 report on negative energy technologies explains "land taken for afforestation/reforestation or BECCS from either agriculture or production forestry would create economic pressure to convert remaining primary forest to cropland and pasture to meet continued food demand, or to harvest it to meet continued fiber demand."[58] A 2020 *Nature Climate Change* article concluded that because of the enormous increase in energy, water, and land use needed to meet a 1.5°C warming target with BECCS as the main negative energy technology, **"end-of-century food prices are projected to increase" sharply.**[59]

The UK Royal Academy noted in a 2018 review that because of bioenergy's impact on freshwater, nutrient cycles, and food production, "**sustainable deployment of BECCS is likely to be at the lower-end of the range based on the land-area constraints alone**."[60] The 2019 report by World Resources Institute, the World Bank, and UN agreed with a 2014 study that had found, "unless food demand patterns change significantly, **there seems to be little spare land for bioenergy developments without a reduction of food availability.**"[61] The 2019 authors noted "**or, we add, without adverse effects on climate from losses of terrestrial carbon**."

This tradeoff was detailed in a 2015 *Science* article, "Do biofuel policies seek to cut emissions by cutting food?"[62] It found, "Our analysis of the three major models used to set government policies in the United States and Europe suggests that **ethanol policies in effect are relying on decreases in food consumption to generate GHG savings**." Roughly "25 to 50% of the net calories in corn or wheat diverted to ethanol are not replaced but instead come out of food and feed consumption." Had the models included "conversion of forests or grassland to produce some more crops," they would have to add the CO_2 released from the land-use change, "reducing or negating the net offset from producing more crops."

So, while a number of analyses suggest that corn ethanol is about 46% less carbon intensive than gasoline,[63] many "**modeling studies analyzing the GHG implications of using crops for biofuels find little or no GHG savings if they take account of the conversion to agriculture of forests and grasslands necessary to replace the forgone food production**," as the 2019 WRI and World Bank report noted. That report adds, "yet present biofuel policies not only allow but even encourage biofuels to use crops from existing croplands."[64]

A 2022 study examined such land-use conversions and concluded they "caused enough domestic land-use change emissions such that the carbon intensity of corn ethanol produced under the RFS is no less than gasoline and likely at least 24% higher."[65] The study concluded, "**our findings confirm that contemporary corn ethanol production is unlikely to contribute to climate change mitigation**."

The 2019 report notes a CCS system added to an ethanol plant "only captures one-third of the carbon released by the whole process and therefore does not make the production of ethanol beneficial." Indeed, even if corn ethanol with CCS were a little better than gasoline, that isn't the appropriate comparison for investments we should make over the next decade. The world is transitioning towards battery electric vehicles (BEVs) running on electric grids that are decarbonizing more every year.

A new analysis, "Should Transportation Be Transitioned to Ethanol with Carbon Capture and Pipelines or Electricity? A Case Study," makes clear that compared to investments **in ethanol with CCS, investments in vehicle electrification plus renewables reduce more CO_2 at a lower price by far**.[66] And the electrification strategy does so with the least amount of both air pollution and land use. That is, "redirecting investments from carbon capture equipment and pipelines for ethanol refineries to wind and solar farms for powering BEVs will benefit the climate, health, and land use tremendously while saving consumers enormous sums of money."

Thus, the rapidly spreading CCS systems for U.S. ethanol production—over 30 such systems are on track to become operational in 2024[67]—may not even deliver fuel with much lower CO_2 emissions than gasoline. But they will in any case deliver a fuel with far more carbon pollution and air pollution than BEVs running on a cleaner and cleaner grid. Biodiesel fuel is equally problematic.[68]

The 2022 Inflation Reduction Act (IRA) expanded the tax credit for CCS from $50 per ton of CO_2 captured to $85. But the credit can be used by corn ethanol plants, which has become the fastest-growing use for CCS. IRA also boosts the blending subsidy for bioethanol and biodiesel. **Yet from a climate, land, and food perspective the best thing would be to simply phase out biofuels from food crops—and then find a more productive use for the land.** Entrenching a fundamentally unsustainable biofuel system for decades is a tremendous misuse of both money and land.

Many studies find that new cropland has long come at the expense of forests and grasslands, both of which store a great deal of carbon. A 2010 study concluded, "Across the tropics, we find that between 1980 and 2000 more than 55% of new agricultural land came at the expense of intact forests, and another 28% came from disturbed forests."[69] Most of the remaining expansion came from shrubland conversion. Very little comes from previously cleared lands. "As we have demonstrated here," the researchers conclude, "**expansion of the global agricultural land base inevitably means clearing tropical forest and shrubland ecosystems**."

A new satellite map found "fields of corn, wheat, rice, and other crops have eaten up more than 1 million additional square kilometers [250 million acres] of land over the past 2 decades," *Science* reported in 2021.[70] "Half of the new fields have replaced forests and other natural ecosystems that stored large amounts of carbon," including savannas, thereby "accelerating climate change."

In this country, "several studies and federal reports have documented a resurgence in conversion of grasslands and other natural and semi-natural areas to row-crop production," noted a 2020 *Nature Communications* paper.[71] This started "in the mid-to-late 2000s" which "coincided with periods of high commodity prices, rapid buildout of the biofuels industry, and reductions to the extent of federal land conservation programs." Making ethanol from corn was rising sharply. "We find that croplands have expanded at a rate of over one million acres per year." The predominant crop planted on newly cultivated land was corn, and "yields of new croplands were 10.9% lower" than the national average for corn. New soy cropland yields were 8.4% lower than average. The *Washington Post* noted in 2022, "**Roughly two-fifths of America's corn and soybean crops now end up burned in engines**."[72]

So, we should not count on steady yield productivity improvements to limit the land impact of large-scale biomass expansion. The 2020 study "found that croplands are moving onto lower-quality land in less-suitable regions—a dual setback to production gains from cropland expansion." The best crop land was already being used. The study noted that "recent field scale analyses reveal globally significant carbon emissions from cropland expansion in the US."[73]

Indeed, a 2019 study found that "in the US, where new croplands primarily replace grasslands," significant CO_2 was released as a result.[74] **During 2008-2012, cropland expansion was responsible for nearly 3% of U.S. CO_2 emissions**. "Grassland conversion was the primary source of emissions, with more than 90% of these emissions originating from SOC [soil organic carbon] stocks," the authors note. They find that, "emissions from domestic LUC [land use change] are greater than previously thought" and "may be largely irreversible in the near term."

At the same time, the UN Food and Agriculture Organization reported in 2022 that, from 2000 to 2018, **"almost 90% of global deforestation worldwide is due to agricultural expansion."**[75] The main driver is cropland expansion causing nearly 50%.

CLIMATE JUSTICE

Many studies have noted that the world does not have much unoccupied and unused spare land—and so the pursuit of large-scale BECCS will have serious equity and climate justice implications**. "The world's forests and savannahs are not 'empty lands' available for conversion to cultivation—a myth debunked long ago,"** argues a 2021 literature review on "sustainability thresholds for BECCS" in the journal *GCB-Bioenergy*.[76]

The review explains that the supposed "empty lands" are "home to people whose food security and livelihoods critically depend on these ecosystems." The author adds, "Large-scale acquisitions or conversion of such lands have been historically entangled with various forms of colonization and land enclosures, with the effect of dispossessing rural and forest communities and pushing them into low-wage job dependency, migration, or the deadly combination of landlessness and joblessness."

The IPCC's 2022 Sixth Assessment Report on climate mitigation notes that **"afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure."** It is precisely large-scale implementation that is contemplated by the IPCC and others. And land tenure insecurity is all too common.

"In many countries, bioenergy has created serious socio-economic problems regarding land tenure and loss of ecosystem services, and BECCS could experience similar problems especially in developing countries and areas inhabited by indigenous communities," the UK Royal Society note in their 2018 report on *Greenhouse Gas Removal*.[77]

The 2022 *Land Gap Report* analyzed the impact of climate mitigation and land-use changes on indigenous peoples and local communities: "**The vast majority of lands and forests targeted by national and international pledges on climate change mitigation and forest restoration are neither unclaimed nor unused**. They constitute the customary lands and territories of indigenous peoples and local communities."[78]

The report explains that "with few exceptions, the various national climate mitigation pledges have paid little attention to who, in practice, is living on, using and managing the lands involved," much less their existing land rights." It concludes, "**without a social justice lens, any attempt to fulfil the many land-based climate pledges is likely to perpetuate injustices**."

While large pastural areas may appear unoccupied, unused, and of little environmental value—and thus perfect for growing biomass for BECCS—they are actually used by hundreds of millions of people and have great value.[79] **"Pastoralism is key to the maintenance of dryland ecosystem functions and services, including soil fertility, watershed protection, aquifer replenishment … and carbon sequestration,"** the report says. "**Grassy biomes store up to a third of the global stock of CO_2 in their soils**."

SOIL ORGANIC CARBON AND GRASSLANDS

Recent studies highlight the climate harm that can be caused by tree planting that displaces grasslands. "We show that California grasslands are a more resilient C [carbon] sink than forests in response to 21st century changes in climate," explain the authors of a 2018 study.[80] During wildfires, the carbon in trees is released to the atmosphere, while the carbon fixed in grasslands typically stays in the roots and soil. The study concludes: "**Since grassland environments, including tree-sparse rangelands, appear more capable of maintaining C sinks in 21st century, such ecosystems should be considered as an alternative C offset to climate-vulnerable forests.**"

A 2021 *Nature* study looked at data from 108 experiments involving elevated CO_2 to see the impact on carbon storage in plants versus soils.[81] An accompanying news release explained the key finding, "plants will likely play a far less significant role in drawing down carbon than previously predicted."[82] The lead author, Dr. César Terrer, noted that "**When a plant dies, some of the carbon that accumulated in its biomass may return to the atmosphere. In soils, carbon can be stored for centuries or millennia**."

Stanford professor Rob Jackson, a study co-author, added "Soils store more carbon worldwide than is contained in all plant biomass. They need much more attention as we project the fate of forests and grasslands to the changing atmosphere." Terrer concludes, "**it would be a mistake to plant trees in natural grassland and savanna ecosystems**. Our results suggest these grassy ecosystems with very few trees are also important for storing carbon in soil."

And we also shouldn't plant trees in permanently snow-covered areas in Alaska, Canada, the Nordic countries, and Russia. The dark forests would absorb more heat than the white snow did and thus "have a warming effect that exceeds the cooling effect of reducing GHGs," as the National Academy of Sciences explained in 2019.[83] We also shouldn't plant them in wildfire-prone areas, which are expanding due to climate change. **Any real-world BECCS proposal should explain exactly where the several hundreds of millions of acres of trees or energy crops would be planted.**

NOT THE BEST USE OF BIOMASS

By the time we might be ready for large-scale BECCS deployment a decade or more from now, it will likely have little or no CO_2 benefit compared to the alternatives yet cost much more—and have a considerable cost in land, fertilizer, water, and CO_2 already sequestered in trees or soils. That's why a 2020 study on "The future of bioenergy" had two key conclusions.[84] First, "the scale of bioenergy that both provides net climate benefits and can be sustainably produced is more limited than most models and scenarios predict." And second, "**policymakers should limit near-term incentives for land intensive bioenergy**."

A 2018 study found, "**the claimed climate benefits of bioenergy are based primarily on an accounting error that treats biomass as automatically 'carbon free' meaning it counts the benefit of using land or biomass for energy without counting the cost of not using them for other purposes."**[85]

BECCS has a major opportunity cost, since it's not the best use for either land or biomass if the goal is to cutting CO_2. The 2020 study on "The future of bioenergy" notes "**the amount of electricity which can be produced from a hectare of land using PVs [photovoltaics] is at least 50–100 times that of biomass**."[86] Photosynthesis is an inefficient way to convert sunlight into power. The study concludes "When biomass is available as a waste product or as a result of good stewardship practices, the best use of the material is for long-term storage as for example in the construction of buildings."

A 2019 report by Material Economics co-funded by the EU concludes, "**bio-based materials production are the applications where biomass resources typically have the highest value in a net-zero context. This conclusion spans multiple materials (wood products, paper and board, textiles, and chemicals).**"[87] At the same time, "demand for existing applications, such as solid wood products and pulp and paper, is expected to grow in the EU to replace more carbon-intensive materials, such as cement and steel in construction or plastics in packaging." The bottom line is "an increase of demand for biomaterials on the order of 50% thus needs to be accounted for" by 2050. But since the priority use of biomass in mid-century will be feeding 10 billion people in a climate-ravaged world, unlimited biomass won't be available for all purposes. Biomass use will be triaged, and the literature makes clear bioenergy and BECCS are not the uses that are most cost effective and beneficial to the climate.

THE EU AND OTHER COUNTRIES GAME THE SYSTEM

The EU has a controversial accounting system for biomass emissions reductions that "risks creating perverse policy outcomes," noted a 2018 Chatham House research paper.[88] The EU's rule is "that even if using forest biomass for energy does result in net emissions to the atmosphere, these emissions are accurately accounted for within the land-use sector. In effect, **emissions are assumed to occur at the point of harvest, not at the point of combustion, and thus from the energy-sector perspective, forest-based biomass energy is carbon-neutral**."

This rule was criticized in a 2018 letter to the EU Parliament from 800 scientists because it "would let countries, power plants and factories claim credit toward renewable energy targets for deliberately cutting down trees to burn them for energy."[89] The 2021 letter from 500 scientists argued the EU "needs to stop treating the burning of biomass as carbon neutral.[90]

A 2018 *Nature Communications* article explains, "If a country's laws give its power plants strong financial incentives to switch from coal to wood on the theory that wood is carbon-neutral, those power plants have incentives to burn wood regardless of the real carbon consequences."[91] This policy means "**forest owners can be rewarded for the carbon in their trees—so long as they cut them down and sell them for energy. The higher the price of carbon rises, the more valuable cutting down trees will become.**" The 2018 Chatham House paper also notes the system incentivizes bioenergy replacing fossil fuels to reduce CO_2 emissions—"even where this reduction is not 'real'."

But there is no way to know if bioenergy emissions from the importing country are accurately accounted for by the exporting country. As noted earlier, a *New York Times* investigation has already shown that much of the biomass in Europe is coming from illegal and/or unrecorded tree cutting. A 2021 *Washington Post* article found that "An examination of 196 country reports reveals a giant gap between what nations declare their emissions to be vs. the greenhouse gases they are sending into the atmosphere."[92] How giant? "The gap ranges from at least 8.5 billion to as high as 13.3 billion tons a year of underreported emissions." The *Post* found "at least 59 percent of the gap stems from how countries account for emissions from land, a unique sector in that it can both help and harm the climate."

"The plan to save the world from the worst of climate change is built on data," the *Post* writes. "But the data the world is relying on is inaccurate."[93]

So how can the world be sure that bioenergy emissions from the country importing wood are accurately accounted for in the exporting country's land-use sector accounts? The 2022 review by the European Academies' Science Advisory Council identified "**the need to establish an independent institutional system that monitors, reports, and verifies data, and calculates the emissions and energy use that relate to BECCS**. This may also be required to allocate credits for net removals when supply chains cross national borders."[94] This body should track every kind of biomass used for bioenergy and determine what if any net CO_2 benefits will be achieved by 2050 and by 2100.

The U.S. needs its own version of this body because the 45Q tax credit for carbon capture and storage—which was expanded and extended under the 2022 Inflation Reduction Act—awards the credit *per metric ton of "qualified"* CO_2, which is the CO_2 "that you demonstrate, based upon an analysis of lifecycle greenhouse gas emissions (LCA)." The LCA report "must be performed by or verified by an independent third party."[95] The IRS explains how the LCA needs to be done (emphasis added):

> The term "lifecycle greenhouse gas emissions" means the aggregate quantity of greenhouse gas emissions (**including direct emissions and significant indirect emissions such as significant emissions from land use changes**) related to the full product lifecycle, including all stages of product and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished product to the ultimate consumer.

The IRS explains "the LCA will be subject to a technical review by the DOE, and the IRS will determine whether to approve the LCA." The DOE needs to figure out how to set up a technical review panel that has a thorough understanding of all the issues surrounding a BECCS LCA and that is not subject to the same kind of political pressure that left us with so much corn ethanol. Failing that, it's very likely the vast majority of tax credit money claimed by BECCS will not actually advance the cause of slowing global warming.

MITIGATION DETERRENCE

A final challenge to BECCS was described in a 2016 *Science* article on “the trouble with negative emissions” strategies: “if we rely on these and they are not deployed or are unsuccessful at removing CO_2 from the atmosphere at the levels assumed, society will be locked into a high-temperature pathway.”[96] Yet, many climate models do count on a significant amount of BECCS post-2030—allowing them to reduce the amount of mitigation required by technologies like solar, wind, and efficiency this decade (and beyond). If the world bases its actions on such models, then it will greatly overshoot its temperature target.

A 2021 Chatham House report cautions against “over reliance on BECCS” and “imagined offsets” that “could delay or deter emissions reductions.”[97] A 2020 study argues that over relying on greenhouse gas removal strategies, primarily BECCS, could result in **“an additional temperature rise of up to 1.4°C**” (beyond 1.5°C).[98]

“Banking on future technologies such as BECCS to compensate later for inadequate emission reductions today places significant risks on future generations,” explained the European Academies’ Science Advisory Council in 2020. “Failure to deliver the removals anticipated would intensify climate change and require even more extreme measures to contain it.”[99]

The carbon debt created by burning wood from trees worsens the risk of overshoot. The 2018 letter signed by 800 scientists says, “Overall, allowing **the harvest and burning of wood**,” to continue being carbon neutral under EU rules, “**will transform large reductions otherwise achieved through solar and wind into large increases in carbon in the atmosphere by 2050**.”[100] The danger is real: “Time matters. Placing an additional carbon load in the atmosphere for decades means permanent damages due to more rapid melting of glaciers and thawing of permafrost, and more packing of heat and acidity into the world’s oceans.”

Thawing of the northern permafrost could release a tremendous amount of CO_2 along with methane (CH4), which is a much more potent greenhouse gas than CO_2. Other positive feedbacks exist whereby warming releases more greenhouse gases which leads to more warming and more releases. So, if repaying the carbon debt takes decades, then warming could accelerate long before the planted seedlings have any impact. “The IPCC climate models show a cluster of abrupt shifts or tipping points that are likely to be initiated between 1.5°C and 2°C,” notes the 2021 Chatham House report on BECCS.

"The initiation of these tipping points could hugely accelerate climate change and generate catastrophic impacts for people and societies the world over."

A 2021 literature review of "sustainability thresholds for BECCS" concludes, **"it may be irrelevant how much CO_2 is sequestered in the second half of the 21st century by BECCS if runaway feedback loops releasing large amounts of CO_2 are triggered."**[101] A 2019 *Nature* article looked at "tipping points in the Earth system—such as the loss of the Amazon rainforest or the West Antarctic ice sheet."[102] The authors note "evidence is mounting that these events could be more likely than was thought."

CONCLUSION

"**In private, scientists express significant skepticism about the Paris Agreement, BECCS, offsetting, geoengineering and net zero**," wrote three leading climate scientists, including Robert Watson, former chair of the Intergovernmental Panel on Climate Change (IPCC), in a 2021 article.[103] "The path to disastrous climate change is paved with feasibility studies and impact assessments."

In the past two decades of soaring global CO_2 emissions, bioenergy with carbon capture and storage (BECCS) emerged as a key part of climate models aimed at keeping warming to 1.5°C or 2°C. Some models assumed that by mid-century it could achieve large-scale negative emissions, removing 5 to 10 $GtCO_2$ or more from the atmosphere each year—10% to 20% or more of total global CO_2-equivalent emissions.

But in the last decade an unprecedented number of scientists and studies have questioned whether BECCS is scalable to such levels, and whether it would generate any net negative emissions at all for decades (if ever)—particularly compared to the increasingly low-carbon power plants it will be competing against.

Dynamic climate modeling, which looks at emissions over decades and can accurately model the impact of scaling up bioenergy and carbon debt—including new results from the En-ROADS model reported here—make clear that significantly scaling up biomass power or BECCS in coming decades would increase global emissions for decades and speed up global warming through 2100 and beyond. **Scaling up BECCS is not carbon removal, but much more like deforestation.** As the 2022 review by the European Academies' Science Advisory Council (EASAC) concluded, "there are substantial risks of it failing to achieve net removals at all, or that any removals are delayed beyond the critical period during which the world is seeking to meet Paris Agreement targets to limit warming to 1.5–2°C."[104]

So, biomass power should not be considered inherently carbon neutral or very low-CO_2 the way solar and wind power are. Nor should putting a CCS system on a bioenergy plant be considered inherently a net negative emissions technology. Only a dynamic analysis can determine that. At the same time, any significant scale up of biopower or BECCS would swallow up vast amounts of land vitally needed to feed 10 billion people mid-century in a climate-ravaged world—land currently occupied by and/or under the rights of indigenous people. **Any real-world BECCS proposal should explain exactly where the several hundreds of millions of acres of trees or energy crops would be planted.** A major study by the World Bank, UN, and others on how to feed the world in 2050 concluded "the proportion of plant material diverted from food and fiber to energy would be unacceptably high—and that **hopes of climate benefits are misplaced. We recommend phasing out bioenergy targets**."

The U.S. is headed toward misspending billions of dollars under the 2022 Inflation Reduction Act (IRA) to support BECCS systems that don't deliver what they promise. **Tax credits for continuing to scale up corn ethanol are an especially bad idea, and, as one, article put it "actually incentivize net increases in CO2, air pollution, land use and consumer costs."**[105] Rather than being carbon neutral (even with CCS) corn ethanol is carbon intensive and should be phased out as we shift to electric vehicles running on renewables. The U.S. urgently needs to "**establish an independent institutional system that monitors, reports, and verifies data, and calculates the emissions and energy use that relate to BECCS**," just as the EASAC recommended for Europe in a 2022 review.[106]

Since BECCS appears very unlikely to provide large-scale net negative emissions by 2050, if ever, the priority climate action this decade and next is to spend trillions deploying proven zero-carbon technologies (like solar, wind, and energy efficiency) while developing and then deploying the next generation of zero-carbon tech.

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Romm spent 5 years in the 1990s working on climate and clean energy solutions at the US Department of Energy. For 3 years, he helped to run the Office of Energy Efficiency and Renewable Energy *ultimately serving as Acting Assistant Secretary, where he oversaw a $1 billion budget for R&D, demonstration, and deployment of climate solutions, including both biofuels and biopower.*

In 2008, Romm was elected a Fellow of the American Association for the Advancement of Science for "distinguished service toward a sustainable energy future." In 2009, Time magazine named him "Hero of the Environment" and "The Web's most influential climate-change blogger" for his work at Climate Progress. Rolling Stone named him one of "100 people who are changing America." Romm has 10 books in the areas of climate change, clean energy, and communications, including an Oxford University Press book that NY Magazine called "the best single-source primer on the state of climate change." His 2004 book, "The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate," was named one of the best science and technology books of 2004 by Library Journal. He has written extensively on bioenergy for more than 15 years. He holds a PhD in physics from M.I.T.

ACKNOWLEDGEMENTS

The contents of this report, including any mistakes, are the responsibility of the author alone. The author would like to thank the Tim Searchinger, Danny Cullenward, Auden Schendler, and Simon Bennett for their comments on various drafts. And finally, the author is very grateful to Michael Mann and Heather Kostick of University of Pennsylvania's Center for Science, Sustainability, and the Media for their tremendous help in bringing this project to fruition.

CITATION: Joseph Romm, *Why scaling bioenergy and bioenergy with carbon capture and storage (BECCS) is impractical and would speed up global warming,* A University of Pennsylvania Center for Science, Sustainability, and the Media White Paper, November 2023. https://web.sas.upenn.edu/pcssm

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[11]Mary S Booth et al., "Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy," *Environmental Research Letters*, February 2018. This paper looked at several scenarios, including one of U.S. wood residues exported as pellets to European bioenergy plants (with no CCS). In this case, more than half of the emissions from burning the residues has not been paid back even after 25 years. If biomass sales and use had kept rising, then the carbon debt would just keep rising. This scenario used forest wood decay rates from a study in North Carolina and actual US pellet exports from 2010–2016 followed by increasing sales through 2024.
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[20]Natural Resource Defense Council, "*Global Markets for Biomass Energy are Devastating U.S. Forests*," September 2022. The review examined "investigations by media, independent watchdogs, and NGOs over the past decade."
[21]BBC, "The Green Energy Scandal Exposed," October 2022. These are the forests of British Columbia, which provide Drax, the second largest producer of wood pellets, with about 20% of their wood. The BBC reported that Drax's sustainability policy is to avoid cutting down and harvesting healthy, primary forest trees. But the BBC also reported that "the company was breaking its own rules" and that Drax's pellet company had been outbidding timber companies for primary forests.
[22]Peter Raven et al., "Letter Regarding Use of Forests for Bioenergy," to the heads of the U.S., EU, Japan and South Korea, February 11, 2021. See also Timothy D. Searchinger, et al, "Europe's renewable energy directive poised to harm global forests," *Nature Communications*, September 2018. This study found, "Wood that reaches a power plant can displace fossil emissions but per kWh of electricity typically emits 1.5x the CO_2 of coal and 3x the CO_2 of natural gas."
[23]National Academies of Sciences, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, The National Academies Press, 2019. The Academies note that even in the case of wood residues there can be a long lasting carbon debt: "if the wood residues would otherwise have been used in a long-lived product such as particle board, it could take decades for the use of this material for bioenergy to have a positive effect of reducing atmospheric CO_2."
[24]Lydia J. Smith & Margaret S. Torn, "Ecological limits to terrestrial biological carbon dioxide removal," *Climatic Change*, February 2013.
[25]Howard Herzog et al., "Comment on 'Reassessing the Efficiency Penalty from Carbon Capture in Coal-Fired Power Plants,'" *Environmental Science and Technology*, May 12, 2016.
[26]Daniel Quiggin, "BECCS deployment. The risks of policies forging ahead of the evidence," Chatham House, London, UK, October 2021.
[27]Bruce Robertson and Milad Mousavian, "The carbon capture crux: Lessons learned," Institute for Energy Economics and Financial Analysis, September 1, 2022.

[28]John D. Sterman et al., "Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy," *Environmental Research Letters*, January 18, 2018. Sterman was part of the team responsible for the new analysis presented here using the En-ROADS system dynamics model.
[29]Roel Hammerschlag, "Uncaptured Biogenic Emissions of BECCS Fueled by Forestry Feedstocks," Prepared for: Natural Resources Defense Council, September 2021. Note that plant emissions are being "reported as of the BECCS plant being in service for 20 years." This analysis was done at the forest landscape, which some studies suggest is a better way to do this type of analysis than looking at individual stands in a forest. See, for instance, Annette L. Cowie et al., "Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy," *GCB Bioenergy*, May 2021.
[30]Natural Resource Defense Council, "A Bad Biomass Bet: Why The Leading Approach To Biomass Energy With Carbon Capture And Storage Isn't Carbon Negative," October 2021. This is "representative of the most common supply chain for biomass to electricity"— the one used by the UK power company Drax, which "sources over 60 percent of its wood from the U.S. Southeast." The life-cycle analysis covered everything from the CO_2 released by forests after harvesting to the CO_2 released by manufacturing wood pellets and shipping them to the UK.
[31]Climate Interactive, "The En-ROADS Climate Solutions Simulator," accessed November 2023.
[32]Climate Interactive, "En-ROADS June 2023: Bioenergy," June 1, 2023.
[33]European Academies' Science Advisory Council (EASAC), "Forest bioenergy update: BECCS and its role in integrated assessment models," February 2022. See also "About EASAC," on the EASAC website. The EASAC consists of the 27 national science academies of the EU Member States, Norway, Switzerland and UK. The report notes "Policy-makers should suspend expectations that BECCS can deliver significant CDR removals by 2050 until models have identified the sensitivity of atmospheric CO_2 levels to different feedstock payback times and can be confident that time-related targets can be achieved."
[34]UN IPCC, *Climate Change 2022: Mitigation of Climate Change,* Working Group III contribution to the Sixth Assessment Report, 2022.
[35]International Energy Agency (IEA), *Energy Technology Perspectives 2017*, June 2017. The EIA's analysis "was informed by a high-level workshop with participation from climate scientists and technology experts" in 2016.
[36]IEA, *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach 2023 Update*, September 2023.
[37]Neil Bird et al., *Using a Life Cycle Assessment Approach to Estimate the Net Greenhouse Gas Emissions of Bioenergy*, IEA Bionergy, 2011.
[38]Alessandro Agostini et al., *Carbon accounting of forest bioenergy: Conclusions and recommendations from a critical literature review*, Joint Research Centre (JRC) of the European Commission, January 2014.
[39]IEA Bionergy (2011) notes "A reference energy system should be chosen that is realistically likely to be displaced by the bioenergy system," explains the report. Another option is "comparing the GHG emission of the bioenergy system with the GHG emissions for the best available fossil energy technology." Back in 2011, this was natural gas, and so the study explains, "assuming natural gas was being displaced would give a conservative estimate of emission reduction." It also noted, "Alternatively, a non-fossil option may be selected as the relevant reference energy system," such as renewables or nuclear.
[40]By "emissions rate well below natural gas," I mean the baseline emissions rate of natural gas plants where there is very little leakage of natural gas (which is mostly methane and a very potent greenhouse gas). In the real world, leakage rates can be quite and the total lifecycle GHG emissions can rival coal.
[41]By 2030, the vast majority of new plants will be renewables plus nuclear, with some new natural gas with CCS (and possibly some regular gas plants)—as well as simply putting some CCS on existing coal or gas. Of course, it's possible that CCS proves not to be practical, affordable, and scalable by 2030, but that would also mean BECCS would be too.
[42]IPCC, *Climate Change 2022: Mitigation of Climate Change, Summary for Policymakers*, Working Group III contribution to the Sixth Assessment Report, 2022.
[43]Vaclav Smil, "Energy at the Crossroads," OECD Global Science Forum, May 17-18, 2006. For a similar calculation, see Niall Mac Dowell et al., "The role of CO_2 capture and utilization in mitigating climate change." *Nature Climate Change*, April 2017.
[44]Michael Cembalest, *2021 Annual Energy Paper*, JP Morgan Asset and Wealth Management, 2021
[45]Hiroko Tabuchi and Brad Plumer, "Is This the End of New Pipelines?" *New York Times*, published July 8, 2020. The articles notes that in 2020, the Atlantic Coast natural gas pipeline was canceled "after environmental lawsuits and delays had increased the estimated price tag of the project to $8 billion from $5 billion."
[46]Benoît Morenne and Joe Barrett, "A New Nimbyism Blocks Carbon Pipelines," *Wall Street Journal*, September 30, 2023.
[47]Jeffrey Tomich, "Developer scuttles plans for Midwest CO2 pipeline," *Greenwire*, October 20, 2023.
[48]E. Larson et al., *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, Final report, Princeton University, October 29, 2021.
[49]National Academies of Sciences (NAS), *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*, The National Academies Press, 2015.

[50]U.S. Department of Energy, "Biomass Feedstocks and Logistics," in Chapter 7 of *Quadrennial Technology Review 2015*, January 2016.
[51]Eric F. Lambin et al., "Global land use change, economic globalization, and the looming land scarcity," *Proceedings of the National Academy of Sciences,* February 2011.
[52]Tim Searchinger et al., "Does the world have low-carbon bioenergy potential from the dedicated use of land?" *Energy Policy*, November 2017.
[53]Peter Potapov, et al., "Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century," *Nature Food*, 2022.
[54]Kate Dooley et al., *The Land Gap Report*, November 2022, Available at: https://www.landgap.org/.
[55]Jordan Hristov et al., "Analysis of climate change impacts on EU agriculture by 2050," Joint Research Centre (JRC) of the European Commission, May 2020.
[56]Joseph Romm, "The next dust bowl," *Nature*, October 2011.
[57]UN Food and Agriculture Organization (FAO), *The state of the world's land and water resources for food and agriculture–Systems at breaking point*, 2021.
[58]National Academies of Sciences, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, The National Academies Press, 2019.
[59]Jay Fuhrman et al., "Food–energy–water implications of negative emissions technologies in a +1.5 °C future," *Nature Climate Change*, August 2020.
[60]UK Royal Society and Royal Academy of Engineering, *Greenhouse gas removal*, September 2018
[61]Bojana Bajželj et al., "Importance of food-demand management for climate mitigation," *Nature Climate Change*, August 2014.
[62]Timothy D. Searchinger, "Do biofuel policies seek to cut emissions by cutting food?" *Science*, March 2015.
[63]Melissa J Scully, "Carbon intensity of corn ethanol in the United States," *Environmental Research Letters*, March 2021.
[64]World Resources Institute, World Bank, UNEP, UNDP et al., *Creating a Sustainable Food Future*, July 2019.
[65]Tyler J. Lark et al., "Environmental outcomes of the US Renewable Fuel Standard," *Proceedings of the National Academy of Sciences*, February 2022. The study also looked at other life-cycle analyses of corn ethanol greenhouse gas (GHG) emissions, including the EPA's, and found that "incorporating the domestic LUC [land-use change] emissions from our analysis into other fuel program estimates similarly annuls or reverses the GHG advantages they calculate for ethanol relative to gasoline."
[66]Mark Z. Jacobson, "Should Transportation Be Transitioned to Ethanol with Carbon Capture and Pipelines or Electricity? A Case Study," *Environmental Science & Technology*, October 26, 2023.
[67]The Global CCS Institute, "Facilities Database," accessed November 2023.
[68]Biodiesel made from palm oil is more problematic than bioethanol. It requires much more land per mile driven and has caused considerable destruction of carbon rich peatland forests in Southeast Asia. The *New York Times* wrote in a 2018 that "six of the world's leading carbon-modeling schemes, including the E.P.A.'s, have concluded that biodiesel made from Indonesian palm oil makes the global carbon problem worse, not better." See Abrahm Lustgarten, "Palm Oil Was Supposed to Help Save the Planet. Instead It Unleashed a Catastrophe," *New York Times*, November 20, 2018.
[69]H. K. Gibbs et al., "Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s," *Proceedings of the National Academy of Sciences*, August 2010. This study analyzed "the rich, pan-tropical database of classified Landsat scenes" created by the FAO to track agricultural expansion across major tropical forest regions.
[70]Gabriel Popkin, "Cropland has gobbled up over 1 million square kilometers of Earth's surface," *Science,* December 2021. These researchers also used "data from the U.S. Geological Survey/NASA Landsat program" for their map. See also Peter Potapov et al., "Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century," *Nature Food*, December 2021.
[71]Tyler J. Lark et al., "Cropland expansion in the United States produces marginal yields at high costs to wildlife," *Nature Communications*, September 2020.
[72]David Fickling, "It's Time to Get Biofuels Out of Your Gas Tank Analysis," *Bloomberg*, June 9, 2022
[73]Tyler J. Lark et al. (2020) noted "the large area of long-term grassland conversion we identified provides strong evidence of widespread clearing of previously undisturbed lands."
[74]Seth A Spawn et al., "Carbon emissions from cropland expansion in the United States," *Environmental Research Letters*, April 2019. See also Zhen Yu et al., "Largely underestimated carbon emission from land use and land cover LULAC] change in the conterminous US," *Global Change Biology*, July 2019. This study reexamined a "commonly used" land-use data set (LUH2) with the help of "a new high-resolution multisource harmonized national LULCC database." Their analysis "implies that previous C budget analyses based on the global LUH2 dataset have underestimated C emission in the United States."
[75]UN Food and Agriculture Organization (FAO), *Global Forest Resources Assessment 2020 Remote Sensing Survey*, May 2022. See also FAO, "FAO Remote Sensing Survey reveals," 2022.

[76]Felix Creutzig et al., "Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments," *GCB Bioenergy*, February 2021. See also Anthony Young, "Is there really spare land? A critique of estimates of available cultivable land in developing countries," *Environment, Development and Sustainability*, March 1999.
[77]UK Royal Society and Royal Academy of Engineering, *Greenhouse gas removal*, September 2018.
[78]Kate Dooley et al., *The Land Gap Report*, November 2022, Available at: https://www.landgap.org/. The authors argue that while indigenous peoples (IP) and local communities (LC) "exercise customary rights to at least half of the world's lands, less than 20 percent of this area is formally recognized as owned by or designated for communities, rendering them and their territories vulnerable to the surging global demand for land."
[79]*The Land Gap Report* (2022) adds, "pastoralism is a significant customary IP and LC livelihood activity. Pastoralism occupies vast land areas in many countries—areas that are particularly vulnerable to global climate and restoration pledges." Pastoralism is the use of large, vegetated pastures for grazing. For indigenous peoples and local communities, "pastoralism is both an economic activity and a form of cultural identity. It is the predominant livelihood support system practised in Africa's arid and semi-arid lands, occupying about 43 percent of the continent's total land mass, with at least 50 million people directly dependent on livestock for subsistence."
[80]Pawlok Dass et al., "Grasslands may be more reliable carbon sinks than forests in California, *Environmental Research Letters*, July 2018
[81]César Terrer et al., "A trade-off between plant and soil carbon storage under elevated CO_2," *Nature*, March 2021.
[82]Stanford University news release, "Soils or plants will absorb more CO_2 as carbon levels rise – but not both, Stanford study finds," March 24, 2021.
[83]National Academies of Sciences, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, The National Academies Press, 2019.
[84]Walter V. Reid *et al*., "The future of bioenergy," *Global Change Biology*, January 2020.
[85]Tim Searchinger, "Global Consequences of the Bioenergy Greenhouse Gas Accounting Error," In Oliver Inderwildi and Sir David King (eds), *Energy, Transport, & the Environment*, Springer, 2018. See also, Richard Birdsey *et al.,* "Climate, economic, and environmental impacts of producing wood for bioenergy," *Environmental Research Letters*, April 2018. The study notes, "Biomass supplies are finite and proposed large increases in biomass uses for energy may reduce the availability of wood for use in long-lived wood products which keep carbon out of the atmosphere for longer and can achieve greater substitution benefits than bioenergy uses." For instance, in building construction, wood can sometimes substitute for steel, whose production generates a lot of CO_2. And wood used in construction sequesters its carbon for a long time.
[86]Walter V. Reid *et al*., "The future of bioenergy," *Global Change Biology*, January 2020.
[87]Material Economics, *EU Biomass Use In A Net-Zero Economy: A Course Correction for EU Biomass*, 2021. The report notes, "bio-based materials have a unique role to play in carbon management of materials. Not least, they can provide an alternative to fossil carbon" for many petrochemicals. "Bio-based options are often cost-competitive relative to … many bioenergy applications." In one analysis "the future chemicals sector would use more biomass than is used in all of power generation, road transport, and industry today."
[88]Duncan Brack et al., "Woody Biomass for Power and Heat: Demand and Supply in Selected EU Member States," Chatham House, London, UK, June 2018. Europe's accounting system borrows from the IPCC's "reporting rules intended to avoid double-counting."
[89]John Beddington et al., "Letter From Scientists To The Eu Parliament Regarding Forest Biomass," January 14, 2018.
[90]Peter Raven et al., "Letter Regarding Use of Forests for Bioenergy," to the heads of the U.S., EU, Japan and South Korea, February 11, 2021.
[91]Timothy D. Searchinger, et al., "Europe's renewable energy directive poised to harm global forests," *Nature Communications*, September 12, 2018.
[92]Chris Mooney, et al., "Countries' climate pledges built on flawed data, Post investigation finds," *Washington Post*, November 7, 2021. The article explains that the full gap (between a country's declared emissions and their actual emissions) "is the result of questionably drawn rules, incomplete reporting in some countries and apparently willful mistakes in others — and the fact that in some cases, humanity's full impacts on the planet are not even required to be reported."
[93]Malaysia's report to the UN on its greenhouse gas emissions, "reads like a report from a parallel universe," writes *The Post*. That report "suggests that Malaysia's trees are absorbing carbon four times faster than similar forests in neighboring Indonesia." This claim "has allowed the country to subtract over 243 million tons of carbon dioxide from its 2016 inventory — slashing 73 percent of emissions from its bottom line." *The Post* reports that "Malaysia's government has downplayed the palm oil industry's climate impact across several categories in its U.N. reports" putting it at odds with "the scientific conclusion that its oil palm industry is releasing huge amounts of carbon."

But it's not just Malaysia. "A key area of controversy is that many countries attempt to offset the emissions from burning fossil fuels by claiming that carbon is absorbed by land within their borders," *The Post* reports. "U.N. rules allow countries, such as China, Russia and the United States, each to subtract more than half a billion tons of annual emissions in this manner, and in the future could allow these and other countries to continue to release significant emissions while claiming to be 'net zero'."

[94]European Academies' Science Advisory Council (EASAC), "Forest bioenergy update: BECCS and its role in integrated assessment models," February 2022. Similar oversight suggestions have been made in Daniel Quiggin, "BECCS deployment. The risks of policies forging ahead of the evidence," Chatham House, London, UK, October 2021.

[95]Internal Revenue Service, "Instructions for Form 8933: Carbon [Di]Oxide Sequestration Credit Section," Revised December, 2022. The amount of CO2 "must be measured at the source of capture and verified" where it is injected back into the ground. "The measurement and written LCA report must be performed by or verified by an independent third party." The IRS explains the submission for the tax credit must include "a statement documenting the qualifications of the independent third party, including proof of appropriate U.S. or foreign professional license, and an affidavit from the third party stating that it's independent from you."

[96]Kevin Anderson and Glen Peters, "The trouble with negative emissions," *Science*, October 14, 2016.

[97]Daniel Quiggin, "BECCS deployment. The risks of policies forging ahead of the evidence," Chatham House, London, UK, October 2021.

[98]Duncan McLaren, "Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques," *Climatic Change*, May 2020.

[99]European Academies' Science Advisory Council (EASAC), "Forest bioenergy update: BECCS and its role in integrated assessment models," February 2022.

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[103]James Dyke, Robert Watson, and Wolfgang Knorr, "Climate scientists: concept of net zero is a dangerous trap," *The Conversation*, April 22, 2021.

[104]European Academies' Science Advisory Council (EASAC), "Forest bioenergy update: BECCS and its role in integrated assessment models," February 2022. The EASAC consists of the 27 national science academies of the EU Member States, Norway, Switzerland and UK. The report notes "Policy-makers should suspend expectations that BECCS can deliver significant CDR removals by 2050 until models have identified the sensitivity of atmospheric CO_2 levels to different feedstock payback times and can be confident that time-related targets can be achieved."

[105]Mark Z. Jacobson, "Biden's Carbon Capture Funding Actually Incentivizes More Emissions and Higher Costs," *The Messenger*, October 26, 2023.

[106]EASAC, "Forest bioenergy update: BECCS and its role in integrated assessment models," February 2022.