Decades of Increased Emissions from Forest-Fueled BECCS

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ABSTRACT: Should climate policies encourage bioenergy with carbon capture and storage (BECCS) using wood from existing forests? Although mitigation pathways in integrated assessment models often rely on BECCS fueled by energy crops, European governments are moving to financially support BECCS sourced instead from existing forests. To estimate its emissions and financial costs, we develop a model that transparently tracks carbon flows from forest to end use and allows policymakers to easily alter assumptions. Modeling multiple wood-sourcing scenarios, we find that BECCS is unlikely to generate negative emissions within 150 years, is likely to produce higher emissions for decades than using natural gas without carbon capture and is likely to increase electricity costs by ~3.5-fold. Only limited improvements occur even if half of the wood comes from residues and half from fast-growing plantations. These results reflect that most emissions occur before the power plant and therefore cannot be captured, and that wood has twice the carbon intensity of natural gas and generates electricity less efficiently. These results counsel against emerging BECCS policies, and our easy-to-use model allows policymakers to evaluate results and different scenarios themselves.

MAIN

European and other governments have adopted or are considering large support through subsidies or emissions trading systems for bioenergy with carbon capture and storage (BECCS) that would rely on wood harvested from existing forests (Supplementary Information). Although BECCS also plays a major role in many mitigation pathways in integrated assessment models (IAMs), high-yielding energy crops are assumed to supply the primary biomass in virtually all such scenarios[1–3 4 5]. These energy crop potentials are commonly based on converting pasture or tropical savannas to energy crops or assume cropland becomes available in a hypothetical future world in which perfect global land use regulation prevents conversion of high-carbon lands: this forces large yield gains, rather than land conversion, to meet any increasing agricultural demands.[2,3 6] Proposals to move forward with near-term BECCS fueled from existing forests may have been influenced by IAMs but are not in IAM pathways and raise foundational questions: (1) would forest-based BECCS achieve its stated purpose of negative emissions or even any greenhouse gas (GHG) reductions over reasonable time periods; and (2) what are reasonable estimates of the financial costs?

To address these questions, we developed a transparent model, BECCS-WOOD, with easily altered parameters to allow stakeholders and policymakers to understand and test results across a range of assumptions. It calculates and shows at each step the flow of biogenic (and any fossil) carbon to and from the atmosphere as wood is harvested, roots and slash decompose, roundwood is turned into pellets, pellets are burned in a power plant, carbon in flue gases is captured or not captured, and trees regrow. These GHG and financial results can be compared with separate estimates of solar or wind. Our model also calculates and compares results with use of natural gas. Outputs include net emissions and costs per kilowatt hour (kWh) and, where applicable, costs per ton of CO_2 mitigated relative to natural gas without CCS (NG-NoCCS) and natural gas with CCS (NG+CCS).

Biogenic Carbon: Nearly all papers evaluating BECCS sources from existing forests, treat wood as biogenically carbon neutral[7,8 9,10,11]. This view reflects the original, incorrect premise that although biomass combustion emits carbon (C), these emissions do not contribute to warming if biomass is produced "sustainably"[12]. If combustion emissions are assumed carbon neutral, every ton of captured carbon becomes a negative emission.

Although this idea persists in some literature and policies, including the EU's ETS, it stems from a misunderstanding of IPCC reporting guidance[13,14,15]. The IPCC instructs countries to exclude CO_2 from biomass combustion in national, energy-sector reporting to prevent "double-counting" so long as the same carbon was already counted as a land-use emission at harvest. As the IPCC clarified, "not including bioenergy emissions in the Energy Sector total should not be interpreted as a conclusion about the sustainability or carbon neutrality of bioenergy" and is not appropriate for "industry sectors"[16]. The accounting principle means that biogenic emissions must be counted once not ignored in whatever contexts bioenergy is evaluated, i.e., once in national inventories and once in lifecycle analyses. Claims that wood is carbon neutral because other forests in a region are growing are similarly incorrect: as emphasized by the European Academies' Science Advisory Council[17], this background growth cannot be attributed as an offset to harvest-induced emissions because it would occur regardless of bioenergy use.

Several papers have evaluated wood bioenergy without CCS while properly accounting for biogenic carbon (some listed in ref [18]), but few analyze BECCS. BECCS does alter the calculation. Potential differences have even led the UK government to announce an intent to support BECCS while reducing support for bioenergy from wood without CCS (Supplementary Information). However, while BECCS captures some biogenic carbon, more biogenic carbon is still released.

What distinguishes biogenic from fossil carbon is that the harvest of wood and forest management can increase forest growth rates. If not harvested, nearly all forests would continue growing, but for most forest types, growth in decades post-harvest is faster than ongoing growth if unharvested. This difference is the "harvest-enhanced growth," which can offset a portion of the carbon debt created by harvest and use. Our model factors this in. Net emissions of BECCS are ultimately based on how much carbon is released versus stored in the forest or underground.

Time: Because net emissions change over time, carbon accounting must reflect temporal dynamics. BECCS-WOOD uses two transparent approaches. The first is a "single use" method, which treats each year of bioenergy as a stand-alone event and evaluates net emissions 30 years after that event. Because it factors in forest-enhanced growth, focusing on 30-year outcomes is generally more favorable to bioenergy than evaluating emission only in the year of harvest and combustion. Using 30 years also expresses this added forest growth with a single intuitive parameter: the share of felled carbon that is recaptured within 30 years via enhanced growth stimulated by harvest and any associated management.

Choice of a 30-year horizon reflects policy preferences for earlier mitigation and can serve as a transparent surrogate for time discounting[19]. This choice reflects how present U.S. biofuel policies are addressing time for direct or indirect land use change, while European policies use 20 years[6]. Any policy choice without time limits or discounting in some way would inappropriately value measures that increase warming for decades before reducing emissions as equivalent to those that achieve immediate reductions. (See additional discussion in Supplementary Information.)

Our second, "sustained program" approach assumes the bioenergy/BECCS system operates annually and calculates cumulative emissions each year up to 150 years. For each year, the model also calculates the average, cumulative emissions intensity (cumulative net emissions incorporating forest-enhanced growth divided by cumulative kWh). This reveals how long bioenergy would need to continue before cumulative emissions match those of natural gas alternatives or reach zero.

Categories of parameters controlling emissions and energy output: BECCS-WOOD, provides four groups of alterable, physical parameters. (Methods define each parameter in detail, illustrate mathematic interactions, and identify sources of defaults.)

The first group captures forest-sector carbon losses from decomposing roots, uncollected residues, and mortality of nearby vegetation. These are governed by root/shoot ratios, slash rates, residue harvest fractions, ancillary mortality rates, and decay rates. Even assuming half of residues are harvested, one third or more of felled wood typically remains in forests to decompose.

The second group determines other pre-power plant emissions and includes fossil fuels used in harvest, processing, and transport (~8% of felled carbon in our default) and carbon lost when roundwood is converted into pellets (typically ~20% of removed roundwood, which is ~15% of felled wood). (If wood is not pelletized, drying and transport losses decrease, but conversion efficiencies in power plants drop substantially.)

The third group dictates power-plant energy output and carbon losses, and includes parameters for electricity or CHP conversion efficiency, the CCS energy penalty, and the fraction of carbon captured from flue gases. Although many studies assume 90% capture, we set 85% as a realistic default reflecting the lack of continuous operation of CCS at peak efficiency.

Table 1: Changeable Parameters for all Bioenergy Scenarios **(All units are ratios; unfilled cells mean the scenario uses the default parameter.)**

Parameter	Defaults	Secondary Forest to Intensive Lobblolly	Existing Int. Lobblolly	Existing Int. Loblolly + 50% wood from residues	N.E. U.S. Forests	U.S. Douglas Fir	U.S. avg	Germany Average	Global Average	CHP Germany	CHP U.S. Average	CHP Extreme
Root:shoot biomass ratio	23:100			23:100	18.4:100		23:100					
% slash (slash rate of ABG carbon)	30%	30%	20%	20%	37%		30%		20%			
% of slash harvested	50%			250%								250%
Carbon loss from ancillary mortality (as % of harvested wood)	8.5%	4.25%	4.25%	4.25%			7%	4.25%	4.25%			
Carbon lost in bark and processing into pellets (% of roundwood and residues harvested)	22%											
GHG intensity of supply chain fossil fuel use (kgCO$_2$e/tonne fuel/tonne fuel DM)	268											
Biomass power efficiency (no CCS) (kWh electricity/kWh of wood pellets)	36%									30%	30%	
Biomass heat efficiency for CHP (no CCS). Set to zero for electricity production only.	0%									45%	45%	
Carbon capture % by CCS	85%									85%	85%	90%
Carbon capture energy efficiency penalty % (subtracted from biomass/power conversion efficiency)	11.1%									5.6%	5.6%	5.6%
Forest-enhanced growth as fraction of all felled wood	39%	38%	57%	57%	0.0%	31.%	36.%	18%	39%	18.0%	36%	60%

The fourth group governs harvest effects on forest growth and carbon-debt repayment. Under the single-use framework, a single "harvest-enhanced growth" parameter summarizes net regrowth over 30 years. For example, if a hectare sequesters 70 tC over 30 years after harvest but would have sequestered 35 tC if left unharvested, the net regrowth is 35 tC. If the felled live biomass contained 100 tC, the enhanced regrowth parameter is 35/100 = 35%**.** Under the sustained-program framework, the model applies a time-dependent function to estimate annual harvest-affected changes in growth over 150 years.

These results can be compared with independent estimates of those of solar and wind, but because of claims that their potential deployment is limited, the model also compares bioenergy) against natural gas electricity or natural gas CHP (each with and without CCS). Users can specify natural gas supply-chain emissions, natural gas conversion efficiencies, and NG+CCS capture rates. Users also specify the NG+CCS energy penalty, which is lower than for BECCS because natural gas plants release less CO_2 per kWh, requiring less CO_2 capture.

Economic outcomes depend on these biophysical parameters and on user-defined cost inputs. Most important are natural gas and wood pellet prices, and users also specify capital and operating costs per kWh. For CHP, the model uses a cost multiplier relative to power-only plants per unit of fuel. (Despite higher costs, higher total energy output of CHP reduces costs per unit of energy output.) Sensitivity functions allow fuel prices to vary by +50% or −33%.

RESULTS

Although model users can easily create their own scenarios, we model a variety of wood supply scenarios, each with and without CCS, and for power only or for CHP. Table 1 shows the modeled scenarios and key input parameters. (The worksheet "Scenario Input Data Tables" in BECCS-WOOD identifies sources for each parameter).

Scenarios include wood supplied from average Northeastern U.S. forests, which are subject to frequent selective harvests of naturally regenerated forests, and from German forests which are typically managed using even-aged harvests from plantings. Both are sources of wood pellets today. To explore best results for bioenergy, which occur for managed plantations with fast regrowth rates, we first use clearcutting of highly productive Douglas fir forests from the U.S. Pacific Northwest. We also use fast-growing, highly productive stands of loblolly pine plantations from the Southeastern U.S. This Southeastern scenario assumes that if not harvested, such plantations would continue growing. Because existing plantation wood is already needed to meet other demands, we also model conversion of a Southeastern U.S. secondary forest to intensive loblolly.

Although these scenarios assume that sourcing wood from a particular forest type will result in more wood supply only from that forest type, market forces mean that wood diverted to bioenergy will probably be resupplied from a variety of forest sources. We therefore also provide scenarios from U.S. and Global average wood supply, including both secondary and plantation forests, calculated using the CHARM model in ref [19].

In these scenarios, we assume harvest of half of wood residues, which generally means residues supply ~21.5% of the total wood for pellets. We add an extremely optimistic variation to the intensive loblolly scenario in which residues supply 50% of total wood using wood collected in part from other harvested stands. We also create an Extreme Optimism CHP scenario supplied 50% by residues, and even higher forest-enhanced growth, and higher CCS capture and energy conversion efficiencies.

Single Use Approach: As shown in Table 2, bioenergy without CCS in all scenarios increases emissions per kWh relative to natural gas without CCS (NG-NoCCS) 30 years after combustion. In most scenarios, emissions at least double, and they are 3.7-fold higher in the Northeastern U.S. scenario. Even in the existing loblolly pine scenario, emissions are 56% higher (792 v. 508 gCO_2/kWh), and they remain 16% higher even if half of wood comes from residues.

Although the purpose of BECCS is to achieve negative emissions, almost no single use scenario achieves them (Table 2 and Figures 1 and 2). The exception combines harvesting from existing intensive loblolly with 50% of wood from residues. In this scenario, only 20% of carbon captured by CCS is a negative emission in power-only plants; the remaining 80% just cancels out positive emissions. In the extreme CHP scenario, this percentage rises to 27%.

BECCS also generates higher than or equal emissions even to natural gas without CCS in nearly all scenarios. Using wood from the Northeastern U.S., BECCS emissions are >3-fold emissions of NG-NoCCC. Only use of existing, intensive loblolly pine plantations, with 21.5% or 50% of wood from residues, generates reductions relative to natural gas with or without CCS in the single use calculation.

Sustained BECCS Program Results: If BECCS continues programmatically beyond a single use, climate results become significantly worse both 30 years after the first year of BECCS and for many decades thereafter. Harvesting and burning new wood each year generates a new, instantaneous carbon loss, so the net effects on carbon become worse until the cumulative regrowth catches up with the cumulative carbon loss. (Table 3 shows results for key emissions thresholds, and the "Sustained Programs Calculations" worksheet of BECCS-WOOD shows annual emissions intensities and cumulative emissions by year.)

To illustrate, while the U.S. average scenario for a single use of BECCS results in emissions of 563gCO_{2eq}/kWh thirty-years later, average emissions for a sustained BECCS program 30 years after the first year remain at 820 gCO_2/kWh (3). That is ~60% higher than NG without CCS. BECCS emissions do not decline to the level of NG-NoCCS until year 129. They remain more than double those of NG+CCS at 150 years.

Only our existing intensive loblolly scenarios generate negative emissions within 150 years, yet that only occurs after 64 years with ~21.5% reliance on residues, and emissions remain higher than NG+CCS for 32 years. Sourcing 50% of wood pellets from residues, negative emissions do not occur for 32 years.

Table 2: Emissions, and financial cost intensities of bioenergy use with and without CCS, for power only or for CHP, and relative to natural gas options.

	Emissions Intensities				***Financial Costs***			***BECCS Emission Attributes***	
Biomass Scenario	***Bioenergy Intensity (no CCS)***	***BECCS Net Intensity***	***Difference BECCS – NG-NoCCS***	***Difference BECCS - NG+CCS***	***Incremental cost of CCS (CCS-NG)***	***Ratio of cost BECCS/ NG+CCS***	***Mitigation cost BECCS relative to NG-noCCS*** ***[relative to NG+CCS]***	***Ratio of Gross BECCS emissions to NG-CCS***	***% CCS C Capture Negative Emissions****
POWER ONLY	*gCO_2e/kWH* ***NG intensities: NG-NoCCS =508; NG+CCS=208***				*\$/kWh*	*$\$ \ kWh^{-1}/\$ \ kWh^{-1}$*	*$\$/tCO_2e$ or no saving*	*$gCO2e \ kWh^{-1} / gCO2e \ kWh^{-1}$*	*CO_2 (net negative emissions)/ CO_2 captured by CCS)*
Global average	1,152	576	69	371	\$0.29	2.60x	No saving	7.64x	None
U.S. average	1,143	563	55	357	\$0.29	2.60x	No saving	7.51x	None
Northeastern U.S. forests	1,842	1,576	1,068	1,370	\$0.29	2.60x	No saving	7.66x	None
Germany avg.	1,488	1,062	554	856	\$0.29	2.60x	No saving	7.30x	None
U.S. Douglas Fir	1,293	780	273	575	\$0.29	2.60x	No saving	7.64x	None
Loblolly, convert secondary to intensive	1,143	563	55	357	\$0.29	2.60x	No saving	7.30x	None
Loblolly, existing intensive	792	54	-453	-151	\$0.29	2.60x	\$642 *[\$1669]*	6.72x	None
Loblolly existing intensive + 50% residues	591	*-236*	-744	-442	\$0.29	2.60x	\$390.55 *[\$570]*	3.32x	20%
CHP	***NG-No CCS=358; NG+CCS = 134*** ***Extreme: NG-NoCCS=339; NG+CCS=113***								
Germany CHP	732	400	41	266	\$0.13	1.85x	No saving	4.20x	None
U.S. Avg CHP	515	165	-193	31	\$0.13	1.85x	\$649 [No saving]	3.32x	None
Extreme Optimism CHP	255	*-112*	-451	-225	\$0.13	1.92x	\$294 *[\$499]*	1.97x	27%

Notes & Abbreviations Table 2: Negative numbers in BECCS net intensity are in italics and in mitigation costs column are costs relative to NG+CCS. Emissions intensity columns show bioenergy emissions per kWh, with and without CCS, and differences between BECCS and natural gas options. Financial options show costs of BECCS relative to natural gas, the relative cost of BECCS to adding CCS to natural gas, and the costs of mitigation in $US per tonne of CO_2eq. To understand the results better, BECCS emissions attributes columns show the gross emissions before factoring in harvest-enhanced forest growth, and the percentage of captured carbon, if any, that represents negative emissions. CCS = carbon capture and storage; NG-NoCCS = natural gas without CCS; NG+CCS = natural gas with CCS. Gross BECCS emissions exclude harvest-enhanced growth. Net emissions include harvest-enhanced growth. Values in square brackets [ ] indicate savings relative to NG+CCS. Negative values in red italics indicate net removals from the atmosphere. CHP values of BECCS are compared to CHP values of NG. Extreme CHP emissions for NG vary from other NG CHP because of higher energy conversion ratios designed to reflect the higher ratios assumed in the "Extreme" BECCS CHP scenario.

Table 3: Years after start of sustained use when cumulative BECCS emissions intensities match natural gas intensities with and without CCS or reach zero

BECCS scenario	**Year**		
	=NG-NoCCS ***508 gCO2/kWh***	**=NG+CCS** ***206 gCO2/kWh***	**=Zero**
Power Only			
Global Average & Default	122	Never	Never
U.S. Average	129	Never	Never
Northeastern U.S.	141	Never	Never
Douglas Fir U.S.	110	Never	Never
Intensive Loblolly U.S.	5	32	64
Intensive Loblolly 50% Residues	1	16	32
Germany Average	Never	Never	Never
CHP	***< NG-NoCCS*** ***358 gCO2/KwH***	***=NG+CCS*** ***134 gCO2/kWh***	***=Zero***
U.S. Average	0 *(235gCO_2eq/kWh)*	119	Never
Germany Average	0 (249gCO_2eq/kWh)	Never	Never
Extreme CHP	0 *(154gCO_2eq/kWh)*	6	29

Notes and abbreviations Table 3: Table 3 shows year after start of sustained use of BECCS in which cumulative net emissions intensities of each wood supply and use scenario equal natural gas emissions intensities without CCS (NG-NoCCS), or with CCS (NG+CCS), or reach zero within 150 years analyzed. Cumulative net emissions intensities equal total emissions produced by the use of BECCS since program start divided by total kWh's produced. Italicized emissions intensities in CHP scenarios at year 0 indicate the immediate BECCS emissions. Where other years are shown, BECCS emissions equal the natural gas intensities indicated or reach zero as indicated by the column. The BECCS-WOOD model sustained program worksheet includes a table showing the emissions each year for 150 years and graphing emissions intensities and cumulative emissions by year.

With BECCS CHP, although results are better than from power alone, they remain mostly worse than natural gas. For example, emissions from the U.S. average wood scenario do not match those of NG+CCS for 119 years and are never negative. For our Extreme BECCS CHP scenario, negative emissions only occur in year 29, and only one third of emissions captured by CCS represent negative emissions after 100 years.

Financial Costs: We estimate that BECCS electricity generation would cost an additional \$0.29 per kWh relative to natural gas power at current fuel prices—an increase of ~350%. By comparison, adding CCS to natural gas electricity would add only \$0.04 per kWh (about 33%). In sensitivity analyses, BECCS costs rise to \$0.39 per kWh, and even the most favorable case (high NG, low wood prices) still roughly triples natural gas generation costs.

Using CHP reduces per-unit costs because energy output is higher and our model treats heat and electricity as equivalent. Using a more relevant financial comparison, adding CCS to a CHP plant is about 25% cheaper for the same biomass input than adding CCS to a power-only plant because of a lower energy penalty.

In all but the loblolly and extreme CHP scenarios, BECCS fails to deliver mitigation relative to natural gas with or without CCS. In the intensive loblolly scenario, the cost of CO_2 abatement is \$1,669 per tonne relative to NG+CCS and \$642 per tonne relative to NG without CCS. Even if 50% of feedstock comes from residues, costs remain high (\$570 and \$391 per tonne, respectively). In the most optimistic "Extreme CHP" scenario, mitigation costs are only somewhat lower (\$499 and \$294 per tonne, respectively).

Comparisons to solar and wind: Estimates of the lifecycle emissions, overwhelmingly embodied emissions, range from 10-36gCO_2/kWh for new solar or wind plants[20,21] with European costs for solar and wind, higher than other regions, in the range of \$0.05-0.08.[22] These compare with \$0.41/kWh for BECCS and generally much higher emissions. Only our single use, intensive loblolly scenario with 50% residues has lower emissions for power in 30 years relative to solar or wind, with implied mitigation costs relative to them more than \$1,000/tCO_2eq.

DISCUSSION

The BECCS-WOOD model lets users explore the impacts of fueling BECCS from existing forests by adjusting key assumptions, yet across diverse scenarios, our analysis shows BECCS fails to deliver negative emissions and is expensive. This makes BECCS both more expensive and climate worse than solar and wind. If solar and wind are impractical because of storage or other limitations, BECCS also produces higher emissions at higher costs than antural gas alternatives across realistic scenarios.

The generally higher emissions for BECCS relative to natural gas stem from several inefficiencies. First, for every ton of carbon in wood that reaches a power plant, more than a ton of carbon emissions has occurred, or is committed to occur within 30 years, in the forest or processing. Second, wood releases twice as much carbon per unit of fuel energy as natural gas. Third, in power plants of comparable complexity, bioenergy generates <2/3 the electricity of natural gas because wood burns at lower temperature. These inefficiencies compound, so bioenergy without CCS results in >6-fold the gross emissions of natural gas per kWh.

Adding CCS captures most of the flue gases, but it does so both for natural gas and BECCS, a meaningful fraction remains uncaptured, and doing so introduces a fourth inefficiency: because of wood's carbon inefficiencies, CCS must remove >3x more carbon per kWh. This requires more energy (although the higher concentration of CO_2 reduces this burden somewhat as less energy is required to capture each tonne). Because BECCS supplies this additional energy using wood, all wood's carbon inefficiencies then compound. As a result, for every two tons of carbon captured by adding CCS, almost an additional ton of carbon equivalent is released, roughly halving the mitigation value of CCS. Combined, the four inefficiencies mean even a single year of BECCS results in gross emissions 30 years later that are ~7x those of NG+CCS.

The harvest-enhanced growth rate can offset some emissions over time, but younger forests generally do not grow sufficiently faster than older forests to overcome these far higher gross emissions. This will typically remain true regardless of harvest age. For example, harvesting highly productive Douglas fir at 40 vs.70 years yields similar results. While harvesting older, somewhat slower growing trees generates higher, harvest-enhanced growth in the regrowing forest, doing so releases more carbon at harvest and therefore must repay a larger carbon debt.

These calculations also assume a single use of BECCS, while real programs would operate for many years with worse results. This is true for intuitive reasons. Even if stands harvested in the first year have sufficient enhanced growth to repay their carbon debt by year 30, stands harvested in subsequent years would retain carbon debts for many more years.

Using wood for CHP plants generates modestly better climate results relative to natural gas by reducing the gap with natural gas both in overall energy-conversion efficiency and in the size of the CCS energy penalty, yet wood use remains climate inefficient. For 150 years, CHP BECCS is never carbon negative with average U.S. and German wood supplies, always exceeds NG+CCS emissions intensities with German wood supplies, and has lower emissions than NG+CCS with average U.S. wood only in year 120. High-efficiency CHP is also practically limited because it requires continuous use of both heat and electricity while heat and power demand often do not align.

Our most optimistic scenarios for BECCS, which rely half on fast-growing plantations and half on residues, help reveal that emissions reductions would be limited even with highly favorable assumptions, but we do not consider these optimistic scenarios realistic. Many claims to BECCS benefits assume heavy or even full reliance on forest residues[23,24,25], but wood pellet manufacturers limit this reliance because residues have less consistency than roundwood and higher moisture, ash, and bark contents. A study for the American Forest and Paper Association found that forest residues provide only 12% of wood used for pellets in the Southeastern U.S.[26], so even our lower scenarios greatly exceed this usage rate. Claims for high residue reliance for bioenergy commonly mischaracterize any low-quality wood or sawmill offcuts as residues, but they are nearly all used for paper products or panels or already burned. True forest residues are limited. If BECCS used 100% of potential forest harvest residues in both the U.S. and Europe, residues could supply only 1% of present EU and US electricity consumption (Supplementary Information). And that would require that users overcome many practical challenges, leave no residues for home heating, biofuels or chemicals and contradict new EU nature requirements to leave more dead wood in forests[27].

Reliance on existing fast-growing plantations also does not represent a real-world consequence of BECCS. Rising global wood demands[19] ensure that wood from existing, intensively managed, fast-growing plantations will all or nearly all be harvested and used for other wood products. Even today, plantations do not fully meet wood pellet demands. Diverting more plantation wood to bioenergy would require replacement with more harvests of naturally regenerated forests or their conversion to new plantations with substantially worse climate results. Intensive plantations also have large adverse effects on biodiversity[28] and face resilience challenges from climate change due to drought or pest infestations. BECCS-WOOD does not address those issues.

The EU has plans to adopt policies that award carbon removal credits if CCS is applied to bioenergy power plants that either already exist or would exist even without CCS (Supplementary Information). This is strange because if the bioenergy already exists, applying CCS at best achieves nothing more than applying CCS to fossil emissions. Regardless of whether carbon captured is called mitigation (by applying CCS to fossil emissions) or removals (by applying CCS to biogenic emissions), one ton of CCS equals one ton less atmospheric carbon. However, applying CCS to existing bioenergy will likely generate worse results than applying CCS to existing natural gas because using wood to generate the additional power for the CCS itself generates higher, uncaptured emissions (as discussed above) than using natural gas.

Our results probably underestimate emissions by ignoring soil carbon losses. Studies have found high levels of soil carbon loss with harvesting,[29] including particularly worrisome studies in the Tropics finding ongoing losses post-harvest for many years [30]. Assuming harvests cease, soil carbon would likely take decades to recover, but we omit soil carbon losses because rates of recovery are little explored.

Our results are generally consistent with emissions estimates from the few papers analyzing single BECCS wood supply scenarios using wood from existing forests without assuming carbon neutrality[31] [32] [33]. (See Supplementary Information for further discussion of reference 31).

Whether the world can and should in the future supply BECCS from energy crops grown on tropical savannas or on hypothesized, future surplus agricultural land is a separate question, with its own important conditions and trade-offs. Our transparent model can help stakeholders and policymakers evaluate more immediate policies to support BECCS fueled by existing forests.

Methods:

We developed a spreadsheet model using excel, BECCS-WOOD, to estimate the GHG and financial effects of harvesting and using wood for power generation, and for CHP, with and without CCS. The model provides comparisons with NG and allows users to change key parameters and design their own scenarios. The model calculates emissions from a harvest for a single year's use of wood for energy at a period 30 years after the harvest. This factors in carbon losses from degradation of forest residues and roots and carbon gains for the typically higher growth rates that occur 30 years after harvest. The model also separately calculates the annual effects for up to 150 years of maintaining continuing BECCS (shown in the "Sust. Prog" worksheet of BECCS-WOOD). Supplementary Information describes how to use the model and summarizes the various output tables.

Mathematical Illustration of the Model

The model calculates outputs in a variety of units, including GHG emissions or U.S. dollars (USD) per kwh. To allow for easy comparisons of natural gas and biomass, the model assumes 1 million tC in fuel at the power plant from either fuel, and for biomass, then back-calculates the carbon in trees subject to harvests. (This quantity varies with the parameters governing losses prior to power plant use.) To more intuitively explain the flow of carbon, we illustrate the math below using the single event version of the model, assuming 100 tonnes of carbon in live trees are subject to harvest (including roots).

Carbon emissions in forest due to harvest: The model estimates the following carbon losses in the forest.

Root losses. Model users specify a root:shoot ratio. Our default ratio of 23:100 means 18.7% (23/123) of total tree biomass is in roots, which means 18.7tC in this example (and 81.3tC in above-ground vegetation). Using a half-life of roots after harvest of 10.5 years, 92% of root carbon is lost in 30 years,17.2tC in our example.

Slash losses. Model users specify the slash parameter by the percentage of above-ground tops and branches left behind after harvest. Using our default of 30%, in this example the slash would be 30% of 81.3 tC = 24.4tC. The user specifies the percentage of slash harvested for energy. Using our default of 50%, 12.2 tC in this example is left in the forest. The specified half-life of 11.4 years means 83.9% of this is lost over 30 years, which equals 10.2tC.

Ancillary vegetation mortality losses: Harvesting wood typically kills some adjacent trees. In some forests, these are likely to be saplings but in the Tropics, these are often other large trees and losses are large[34]. Model users specify this ancillary mortality as a percentage of wood subject to harvest. Using a default based on Northeastern U.S. Forest of 8.5%, ancillary mortality in our example equals 8.5tC. Applying the same root/shoot ratios and degradation rates for roots and above-ground slash, 7.1tC are lost.

Summing these losses, for each 100 tons of carbon in live trees subject to harvest, carbon losses equal 17.2 (roots) + 10.42(slash) + 7.1 (ancillary) = 34.5tC. An additional 4.9tC remains undecomposed in the forest after 30 years, and 69.1 tC in wood are sent for pelletizing, including 56.9tC from stemwood and 12.2 tC from residues.

Carbon emissions in wood pellet production & transfer: Wood pellet production loses carbon as bark and other wood is burned for drying. Additional small quantities of wood are also lost in transportation processes. BECCS-WOOD allows users to specify one parameter for the percentage of carbon lost. Using the default factor of 22%, this means losses of 22% * 69.9tC = 15.4tC in our example, and 54.5tC remain in wood pellets that reach the power plant.

To estimate use of wood chips instead of pellets, loss parameters could be adjusted, e.g, some literature finds uncovered wood storage can lead to 10% loss of dry matter[35], and stored chips are also subject to losses. Such scenarios should specify lower energy conversion efficiencies in the power or heating plant.

Fossil emissions in forestry and wood pellet production: Fossil carbon and trace gasses are emitted in managing forests, harvesting, transportation and producing wood pellets. The model specifies these emissions as kg CO_2eq. per tonne of wood pellet fuel. Here we use an estimate of 268.1 kgCO_2eq per tonne of wood pellets, which equals 0.162 t fossil Ceq lost per tC in pellets (assuming 45% C of wood pellets). In this example, that generates 8.8tCeqv of emissions.

Total pre-power plant: Summing, of the 100 tC in trees subject to harvest, C losses equal losses in forest (34.5) + pellet losses (15.4) + fossil (8.8) = 58.7 tCeq and 54.5tC reach a power plant in wood pellets. (The total equals more than 100tC in trees subject to harvest because of fossil emissions and ancillary tree mortality.)

Carbon emitted from the power plant or captured: The model assumes all the carbon in wood pellets reaching the power plant is released through combustion. The user sets the fraction of CO_2 captured by CCS. Using our default factor of 85%, 15% of 54.5tC in wood pellets is lost (8.2tC), and 46.3tC is stored.

Total gross carbon emissions: Total carbon losses over 30 years excluding enhanced forest regrowth, equals 66.7tC. Storage of 45.8tC means CCS captures 41% of total emissions without CCS.

Harvest-enhanced growth: Forest-enhanced growth rates, expressed as a percentage, are based on separate calculations of growth rates, which must be based on forest growth statistics or models. For example, if the unharvested forest would grow and sequester 30 tons of carbon while harvested forest regrows at twice that rate, i.e., 60 tC, the enhanced regrowth is 60 – 30 = 30 tons. Dividing this 30 by the carbon in the felled wood including ancillary mortality (108.5tC) yields an enhanced growth rate of 27.6% and a carbon gain of 30tC.

Net losses: Net emissions subtract forest-enhanced growth from gross emissions. In this example, this means 66.7 – 30 = 36.7tCeq net losses at year 30.

Calculation of kWhs of power or CHP and emissions intensities

The model assumes an energy content of wood pellets of 19GJ/tonne, HHV. Model users specify a conversion efficiency. Our default of 36% is based on reported achievements of the Drax power plant in the UK. This is high for bioenergy power plants and reflects efficiencies achievable for a large facility.

For CCS, model users set the energy penalty, reflecting the power that must be used to operate the CCS. This is expressed as an absolute reduction in the conversion efficiency of the power plant. In our example, the default of 11.6% means an ultimate conversion efficiency for BECCS of 36%-11.6%=24.4%. Assuming 19 GJ/t of wood pellets and C ratio of 45% (to reflect remaining water content), the 53.9tC in wood pellets in our example generates 53.9/.45t pellets * 19GJ = 2,275.9 GJ = 632,183 kWh. A conversion efficiency of 24.4%, generates 154,253 kWh.

Emissions intensities divide net emissions by kWh. In our example, converting net carbon losses of 36.7tCeq to CO_2 (134.6tCO_2) and dividing by 154,253 kWh equals 872 gCO2/kWh.

To estimate effects of a combined heat and power (CHP) plant, the conversion efficiency can be increased, and the energy penalty decreased, and results can be compared with CHP for natural gas.

Outputs from BECCS portion of model alone

Model outputs for each scenario include:

- GHG emissions per kWh electricity
- Biogenic emissions only per kWh
- Fossil emissions only per kWh
- Percentage of biogenic and total carbon captured
- Quantity and percentage of carbon losses occurring (a) in the forest, (b) in processing and transport of wood pellets, (c) in the plant.
- Fossil fuels emissions released as a percentage of carbon captured by CCS

Default BECCS Parameters & Sources

Sources for the parameters in each scenario are provided in the BECCS-WOOD excel file. Default parameter sources are as follows.

Root-shoot ratios and root decomposition rates: The default root to shoot ratio of 23/100 is based on a formula from Huang et. al. (2021) and as then calculated for global average wood harvests using the CHARM model from Peng et al. (2023). Root decomposition rates were derived from a global meta-analysis of coarse and fine roots in woody vegetation types (excluding shrub, mixed, and graminoid)[36]. Assuming 95:5 ratio of coarse to fine roots, we extracted type-specific residence times for conifer (23.8 years; 4.1% annual loss), deciduous broadleaf (3.4 years; 25.6% annual loss), and evergreen broadleaf forests (2.8 years; 30.4% annual loss). Using global forest-type abundances (38% conifer, 29% evergreen, 27% deciduous; Ma et al., 2023), we obtained a global weighted mean root residence time of 10.5 years (9.1%

annual loss). This estimate aligns with another median root residence time of 10.8 years reported by Iversen et al. (2017).

Slash production and decomposition rates: Default slash rates of 30% of above-round biomass are based on IPCC factors for biomass expansion factors and as calculated for a global average using the CHARM model. We estimated slash decomposition rates using a global meta-analysis of carbon fluxes from woody debris across forested continents, climates, and species [39]. The study compiled first-order decay constants (k value, yr^{-1}; Olson, 1963), where larger k values indicate shorter residence time (1/k, yr) and faster turnover. To represent typical global conditions, we extracted the stem decomposition k values from the TRY database (REF), yielding 307 observations with a global median residence time of 16.4 years, equivalent to a half-life of 11.4 years (ln(2)/k) or annual mass loss of 5.9% annual loss under an exponential decay.

Ancillary mortality: Because of limited data, default carbon loss from ancillary mortality of 8.5% of above-ground, mature tree harvest is based on analysis from the U.S. national forest inventory using the SORTIE model described in ref [41] and [42]. This is likely conservative for non-plantations as these forests are selectively harvested and generally harvested efficiently. For selectively harvested tropical forests, which are included in the global average modeled by CHARM, additional ancillary mortality is directly incorporated into the slash rate and is based on Ellis et al.[34] For plantations, because of a lack of data, we assume half of the ancillary mortality rate.

Carbon losses in wood pellet production and transport: Our default of 22% is taken from Roder et al. (2015)[43], which are similar to estimates in Giuntoli et al. (2015)[44] for production losses only, excluding transportation.

Residue harvest percentage: Default residue harvest levels for energy are specified at 50%. A review of minimum sustainability standards for coarse residue retention shows variation from 15% to 70%,[45] but these are minimum legal requirements and do not count fine residues[46]. The EU's recently enacted nature restoration law also requires countries increase dead wood in forests for biodiversity, which implies more residue retention (Art. 12, par. 3 of ref [27]). The selection of 50%, results in a contribution of residues to wood harvest of 21% and is more than the 12% estimate of residue use in ref. [26]. (Residues are true forest harvest residues and exclude materials commonly called “residuals” of sawmill production because these sawdust and offcuts are virtually all useable for other wood products or are otherwise burned for energy in sawmills.)

Default energy conversion efficiencies: Defaults for BECCS power plants are based on data reported by DRAX for its large U.K. powerplant as calculated and reported in Quiggin (2021)[47].

Enhanced regrowth percentage*:* The default of 39.1% is an average of both secondary forests harvests and fast-growing plantations, based on global results from the CHARM model used in Peng et al. (2023).[19]

CCS capture rates: Although the literature commonly assumes 90% capture rates, these rates assume that CCS facilities work 100% of the time plants are operating. For existing CCS plants, CCS has operated significantly below full-time[48] [49]. By this experience, 85% is optimistic. The model also favorably assumes for BECCS no leakage from captured carbon.

CHP plant efficiencies: For default factors, we use 75% energy efficiency for BECCS CHP plants and 85% energy efficiency for natural gas CHP plants. Although higher efficiencies may be technically achievable, differential timing of demand for heat and electricity place limitations on maximizing energy efficiency while keeping a plant operating year-round. Limited summaries of real world performance suggest that 75% is a high end for real operations[50,51].

Energy penalties CCS: The default energy penalty of 11.6% taken from Isoli et al. 2025 assumes biomass penalties are the same as those of coal. For CHP, engineering analyses find that heat generated by the power plant can be used to drive much of the CCS process without sacrificing significant heat production although it is unclear exactly how this will affect efficiencies in action. We here optimistically assume CHP will cut energy penalties in half, i.e., to 5.55%. Some literature, using unproven, innovative designs, suggests energy penalties in CHP plants can be lower, but they assume CHP plants are operated primarily to generate district heating,[52] which sacrifices electricity production and requires reduced operation during warmer months.

Harvested-Enhanced Growth Rates in Scenarios

Harvest-enhanced growth rate sources for different scenarios are identified in the BECCS-WOOD model. In several harvest-enhanced growth rates are taken from U.S. Forest Service estimates of forest growth rates in Hoover, Bagdon & Gagnon (2021)[53]. Northeastern U.S. Forest estimates are from direct measurements of changes in harvested forests in U.S. national forest inventory data and incorporated into the SORTIE model described in Brown et al. (2024)[42]. The data available in this model allows analysis only 15 years after harvests and indicates that in this time, growth rates following a 30% biomass harvest are actually lower than unharvested stands of comparable harvest ages. Because 30 years is the best estimate from this data of the period in which growth rates recover, our estimate of no change in growth rates in this period is beneficial to bioenergy.

Natural gas calculations and default parameters

The model allows comparison to natural gas power plants and CHP plants, with or without CCS using the following parameters. Leakage rates of natural gas (venting, fugitives, flaring) during natural gas extraction, leakage rates during transport. In the default, each is assumed to be 1%. Non-methane production emissions for natural gas production and transport expressed as CO_2e/kwh of natural gas fuel. In the default, this is set at 22gCO2e/kWh based Prussi et al. [54]. The default conversion efficiency for natural gas is 60% based on IPIECA[55] and similar to Prussi et al. (2020)[54] to ensure that efficient biomass plants are compared to efficient natural gas plants. The default CCS rate is assumed to be the same as for BECCS. The default energy penalty is set at 7.6% based in Isoli et al. (2025), and this is cut in half for CHP. All parameters and sources are shown in the Scenario Input Data Tables worksheet of BECCS-WOOD.

Costs and default parameters

The model calculates financial costs per kWh of power or CHP for bioenergy and natural gas plants and per tonne of CO_2eq mitigation if bioenergy power plants reduce emissions. Financial parameter inputs include fuel costs for biomass and natural gas, and one parameter for non-fuel costs for each without CCS. Default factors for non-fuel costs are taken from Fajardy et. al (2021),[56] wood pellet costs for wood pellets are taken from Argus forward prices for 2027 as quoted in Quiggin (2024) [57] and natural gas prices are taken from European averages as reported by the European Commission (2025)[58]. The model also includes a non-fuel cost for CCS, including injection and storage costs, which adds \$0.03 for natural gas and \$0.16 for bioenergy also based on Fajardy et al. (2021).

Because the literature is highly variable about how much CHP adds to the costs of a power-only plan, we adopt a default, increased non-fuel cost of 30%. Because heat has lower economic value, in part because of higher conversion efficiencies, the costs of CHP should not be directly compared with the costs for power only.

Sustained program model methods

The "sustained program" version of BECCS-WOOD is a simple temporal expansion that allows emissions and sinks associated with bioenergy generation to be characterized across ongoing years of bioenergy use. Results include emissions and carbon sequestration in each year from ongoing harvest and the effects of prior harvests. The model then calculates cumulative emissions, cumulative electricity or electricity and heat production in kWh, and cumulative emissions intensity (cumulative emissions/cumulative kWh). The model assumes indefinite continued sourcing using the same scenario and quantity of biomass use as in the first year (i.e. the biomass demand identified in the active scenario in the CCS calculation sheet).

The model identifies four emissions sources that are treated as occurring in the year of harvest: one, emission of CO_2 from wood combusted for biomass drying before pelletization; two, emission of CO_2 from fossil fuel use in the supply chain; three, emission of uncaptured CO_2 from the bioenergy plant.

The model identifies three pools of biomass carbon that are assumed to be subject to exponential decay to CO_2: slash left in the forest after harvest, including wood from ancillary damage to non-target trees; roots left in the forest after harvest; wood lost in transport prior to pelletization.

Harvest-enhanced growth is estimated with a Monod function as in the CHARM model and described further in Supplemental Information.

Data and code availability: The BECCS-WOOD model is included as supplementary data. The data supporting this study are presented in that BECCS-Wood model file or in the references cited for specific parameters. Forest-enhanced growth rates were derived in part from the CHARM model, and parameters for the northeastern U.S. scenario are estimates derived from the plot and tree datasets from the USDA Forest Service Forest Inventory and Analysis program, which can be downloaded at https://research.fs.usda.gov/products/dataandtools/fia-datamart. Summaries of the derivations of the specific parameter values by either model will be provided upon request.

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Figure 1

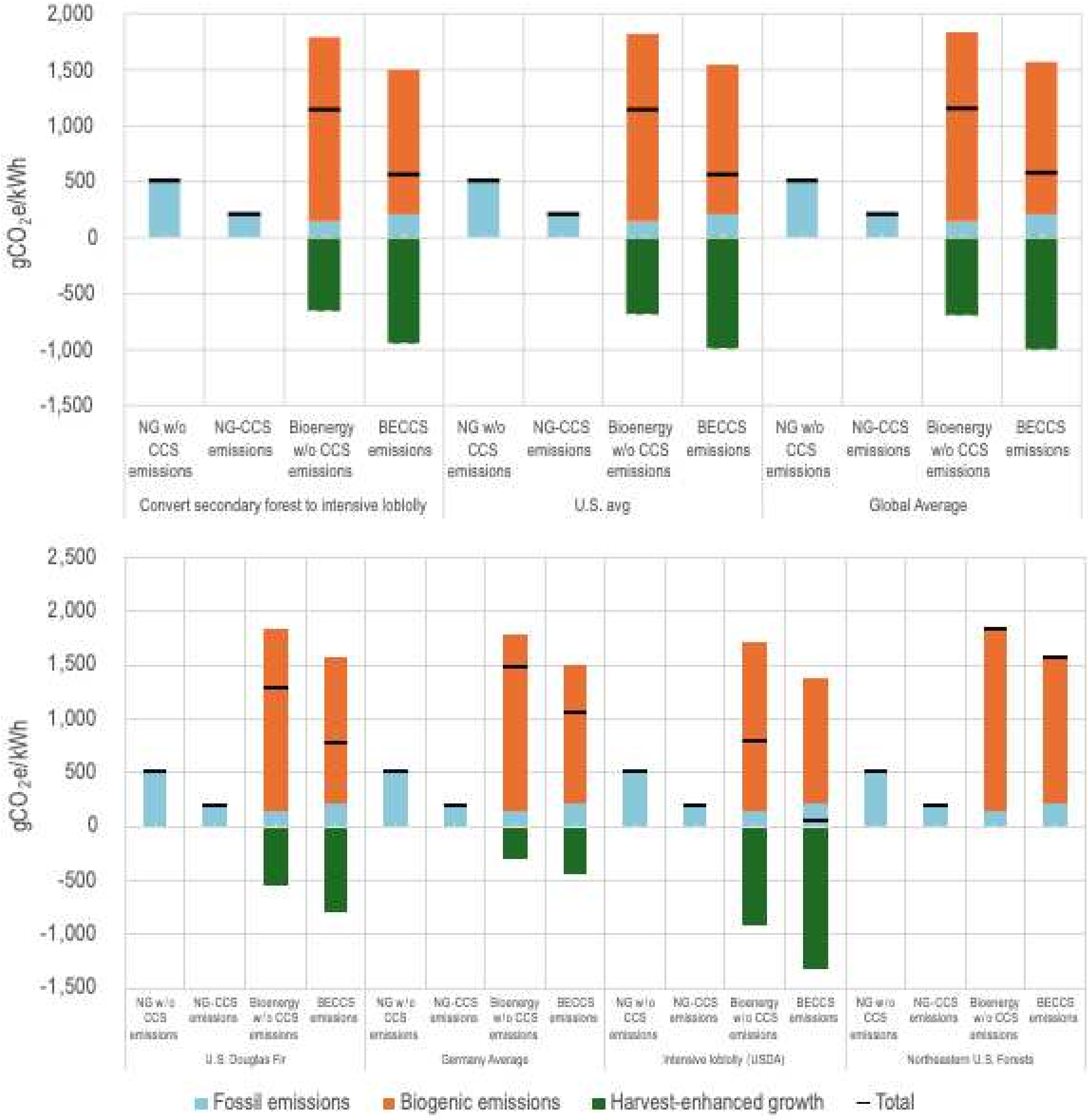
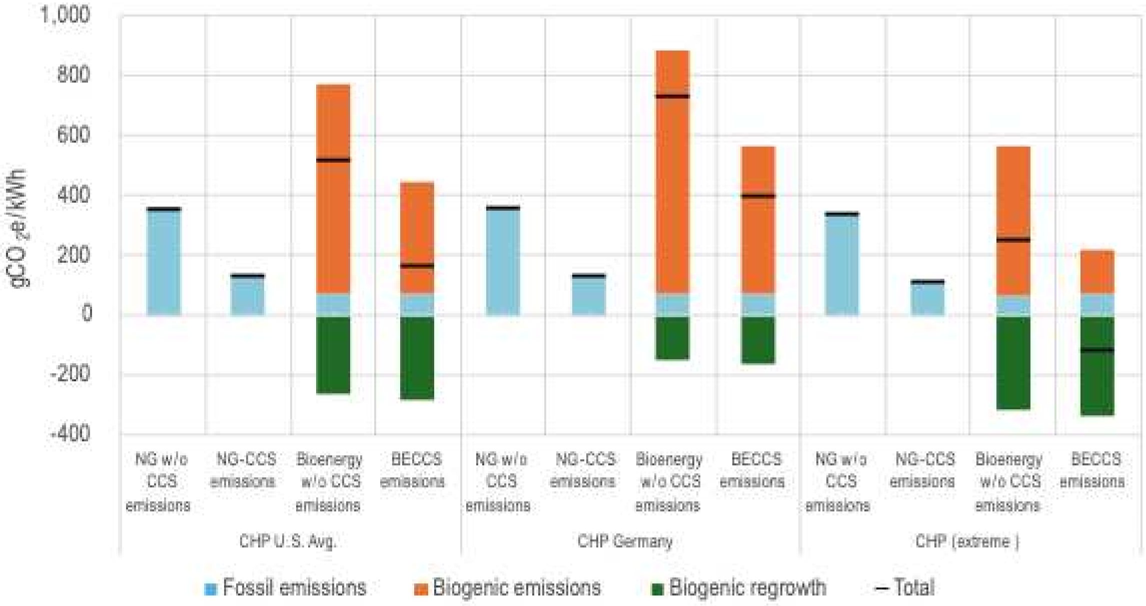


Figure 2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800
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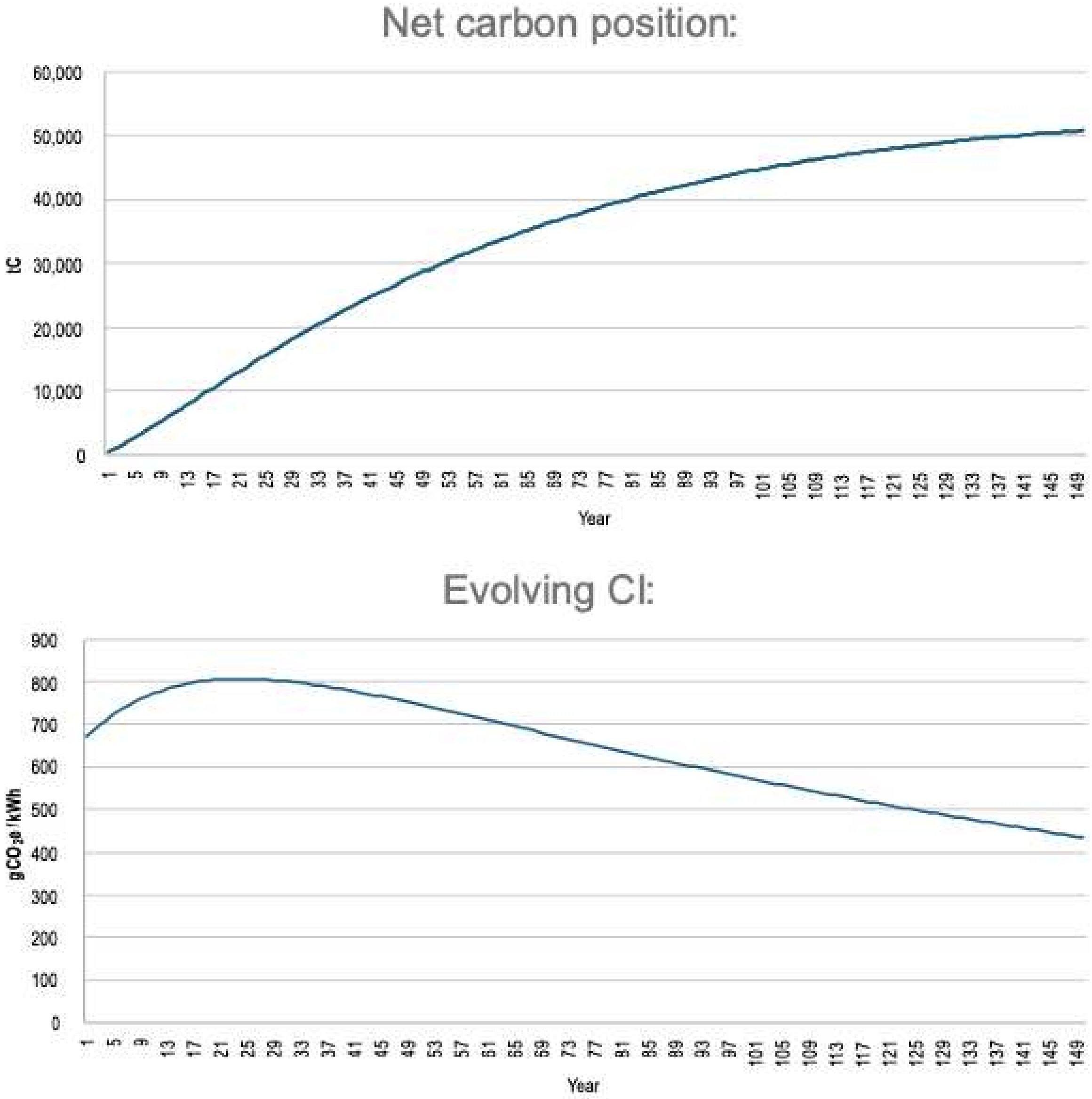
400
200
0
-200
-400
gCO 2e/kWh
NG w/o CCS emissions
NG-CCS emissions
Bioenergy w/o CCS emissions
BECCS emissions
CHP U.S. Avg.
NG w/o CCS emissions
NG-CCS emissions
Bioenergy w/o CCS emissions
BECCS emissions
CHP Germany
NG w/o CCS emissions
NG-CCS emissions
Bioenergy w/o CCS emissions
BECCS emissions
CHP (extreme)
Fossil emissions
Biogenic emissions
Biogenic regrowth
Total

Figure 3


Net carbon position:
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40,000
30,000
20,000
10,000
0
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Year
Evolving CI:
gCO2e / kWh
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800
700
600
500
400
300
200
100
0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149
Year

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