

## Full Length Article

The role of the pulp and paper industry in achieving net zero U.S. CO<sub>2</sub> emissions in 2050Molly Charles, Kanishka B. Narayan<sup>\*</sup>, Jae Edmonds, Sha Yu

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## ABSTRACT

The pulp and paper industry is energy-intensive, making up about 9 % of total United States industrial energy consumption and 2.5 % of U.S. industrial greenhouse gas emissions. The pulp and paper industry is unique among industrial sectors due to its existing reliance on waste biomass to generate energy for mill operations. Pulp and paper mills could theoretically offer opportunities for negative emissions through carbon capture and storage (CCS) technologies along with use of biomass. In addition, the paper sector's use of low-temperature industrial heat creates opportunities for CO<sub>2</sub> reductions through electrification technologies.

We employ the Global Change Analysis Model (GCAM) to evaluate decarbonization pathways for the pulp and paper sector in the United States, as well as the sector's role in a net zero scenario and impacts on the energy, land, and water sectors. The version of GCAM used in this study includes detailed representation of major industrial sectors, including the pulp and paper industry. Representation of the linkage between forest products and paper production allow us to account for upstream carbon emissions, sequestration, and land-use impacts.

Preliminary results under a pathway to net zero U.S. CO<sub>2</sub> emissions in 2050 show that the pulp and paper industry can reach net zero CO<sub>2</sub> emissions before 2050, earlier than the overall energy system, and contribute negative emissions thereafter. Use of fossil fuels is significantly reduced by 2050, shifting to increased electricity use in process heat generation. Consumption of biomass energy in process heat also increases compared to the reference scenario. Though paper production decreases in the policy scenario in response to higher prices of wood products, a high carbon price can incentivize increased use of biomass with CCS and thus paper production. Negative emissions opportunities in the paper industry have impacts on the land sector. Increasing use of biomass accelerates the shift from unmanaged to managed forests, with associated tradeoffs between technological carbon sequestration and natural ecosystem services.

## Introduction

To reach the United States goal of economy-wide net zero greenhouse gas emissions by 2050, every sector must rapidly reduce emissions. In addition to deep reductions in greenhouse gas emissions, technologies and nature-based solutions for negative CO<sub>2</sub> emissions will likely play a key role in balancing out residual emissions and stabilizing global temperatures after reaching net zero emissions.

Industry contributes about a quarter of total greenhouse gas emissions in the United States. Decarbonization of industry thus is critical to comprehensive decarbonization. Industry sectors are heterogeneous and require different approaches to reaching net zero emissions. Detailed representation of industry has been lacking in many integrated human earth system models that have capability to analyze inter-sectoral

dynamics in decarbonization scenarios.

Here, we add representation of the pulp and paper industry to GCAM [1], a technology-rich multisector dynamics model with coupled economic, energy, water, land, and climate systems. The integrated structure of GCAM allows for analysis of the dynamics and interactions across sectors and scenarios, including the upstream land-use impacts of harvesting biomass for paper raw material and energy use. This structure thus allows for the full exploration of the effects of a transition to a low carbon economy and different carbon price schedules on not only on production and prices in the pulp and paper industry, but also on the land system.

In GCAM, 32 regions (which includes the US) also interact through trade, specifically Armington trade (i.e. regions can choose between domestic and imported consumption for several products). Thus, in this

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version of the model, on the forestry side, harvested roundwood (the primary product) is traded between regions in addition to the wood pulp produced. On the energy side, regions trade fossil fuels along with biomass and biomass-based products [2,3].

We find that the pulp and paper industry, due to large existing use of energy generation from waste biomass combustion, has the potential to sequester biogenic CO<sub>2</sub> and contribute negative emissions toward reaching the overall net zero goal. Potential for negative emissions varies widely across regions, as it requires waste biomass from primary pulp production and adequate supply of forest products for both raw material and energy generation. However, opportunities for carbon sequestration in the paper industry has tradeoffs with land use. Availability of paper industry CCS can accelerate the shift from unmanaged to managed forests, with associated impacts on forest carbon storage as well as biodiversity and ecosystem services.

### Background on the U.S. pulp and paper industry

The pulp and paper industry is energy-intensive, making up about 9 % of total U.S. industrial energy consumption in 2021 [4]. Direct greenhouse gas emissions from the pulp and paper sector were 34.9 million metric tons of CO<sub>2</sub> equivalent in 2021, accounting for 2.5 % of U.S. industrial emissions [5]. This figure excludes biogenic carbon emissions, which contributed an additional 118.8 million metric tons of CO<sub>2</sub> in 2016 [6]. The pulp and paper sector is unique among industry sectors due to large quantities of biomass use as an energy source as well as material feedstock.

The U.S. produced 67.5 million tons of paper and paperboard in 2021 [7], down from a peak of 84.3 million tons in 2006. Chemical pulping accounts for the majority (85 %) of pulp production, while mechanical pulping contributes 8 % [8]. Use of recovered paper in the pulp and paper industry has grown significantly, from about 16 Mt in 1980 to 45 Mt in 2021 [7].

Total U.S. paper consumption has declined since the early 2000s (Fig. 1), driven by a steep decline in the use of newsprint (from annual consumption of 12.7 Mt in 2000 to 1.4 Mt in 2020) and printing and writing paper (from 27.6 Mt in 2000 to 10.1 in 2020). Packaging is the largest component of U.S. paper production (42.5 Mt in 2020). Consumption of packaging paper and sanitary paper (7.5 Mt in 2020) has

increased slightly over the past two decades. The U.S. both imports and exports paper products but is a slight net exporter, mainly consisting of packaging paper (with 8.6 Mt of exports in 2020) [7].

As seen in Fig. 1, Over half of the fuel (1126 PJ) used in the pulp and paper industry is residue biomass generated during the production of virgin pulp [9]. The main component of this is black liquor, a byproduct of the chemical pulping process, as well as hog fuel (waste wood and bark) from the debarking and chipping processes. Black liquor is combusted in a recovery boiler to both generate steam and recover inorganic cooking chemicals.

Purchased fuels make up less than half of total energy consumption. US pulp and paper mills consumed 291 PJ of electricity in 2017, used throughout the production process to power machine drives, motors, pumps, and other electrical processes. In addition to purchased electricity, the industry is also the largest self-generator of electricity among U.S. manufacturing sectors, generating about 40.5 TWh of electricity onsite in 2018 (about 30 % of total U.S. manufacturing self-generation) [10]. Steam is used in significant quantities throughout pulping and papermaking, for processes including pulping, cooking, bleaching, and drying.<sup>5</sup> Natural gas is used mainly boilers and lime kilns, and makes up 383 PJ (8 % of total energy use in the sector). To a lesser extent, the paper industry also consumes coal (55 PJ) and oil (8 PJ), used mainly for process heat generation and in lime kilns. Use of biomass energy has increased by 22 % since 2005 [9]. Use of purchased fuels has declined, with a particularly steep drop in use of refined liquids. In 2015, as per the IEA energy balance data, 67 % of the energy required by pulp and paper mills in the US was self-generated. This characteristic of the industry highlight the important role the industry can play under alternative net zero or low carbon transition scenarios.

Among industrial sectors, the pulp and paper industry is generally among the less challenging to decarbonize, due to its existing reliance on self-generated waste biomass energy, cogeneration, and use of low-temperature industrial heat. Previous studies find significant potential for improved energy efficiency in the pulp and paper industry through technology adoption and process optimization. The advancement of high-temperature heat pumps for industrial applications creates opportunities for electrification of process heating, due to the lower temperature industrial heat required by the pulp and paper industry. Over 90 % of process heat demand in the pulp and paper industry is lower

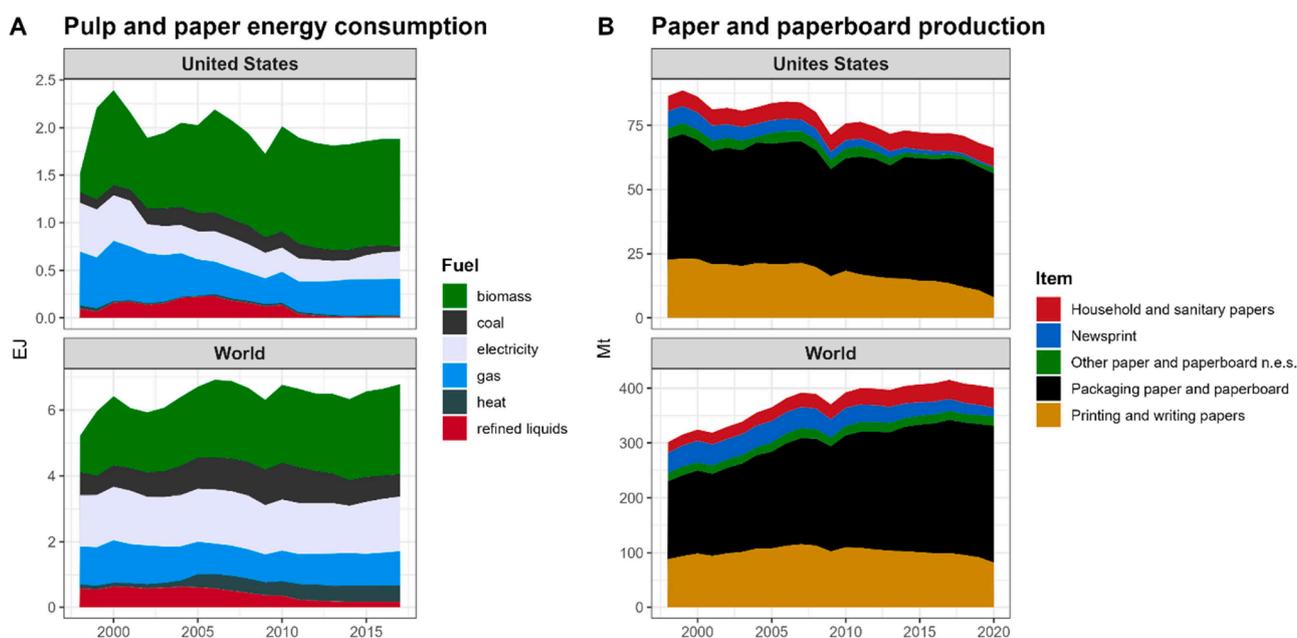


Fig. 1. U.S. and global paper industry energy use, and production by paper product type. Energy data source is the International Energy Agency (IEA) energy balances. Production data source is the Food and Agriculture Organization [7].

than 200 °C, while commercially available heat pumps can supply heat up to 165 °C [11]. Waste heat is produced by several pulp and paper processes, which could be recovered with a heat pump and converted to medium-temperature heat for improved efficiency and lower emissions. Black liquor gasification is also researched as an alternative to the black liquor recovery cycle, which could improve the efficiency of energy recovery [12].

In addition, the pulp and paper sector can theoretically provide opportunities for negative emissions and contribute to reaching the overall net zero target. This can be achieved through the installation of CCS technology along with biomass combustion. As highlighted in previous research, existing biogenic combustion sources provide an initial market for deploying CCS technology [13]. The pulp and paper sector is the largest industrial user of biomass for stationary heat and power in the U.S., and thus offers potential to be an early adopter of engineered carbon capture for net negative carbon emissions.

At the same time, the sector could be affected by challenges related to growing demand for biomass feedstock and land use competition in an economy-wide decarbonization scenario. Decarbonization scenarios after all anticipate a growth in biomass use for energy generation and feedstocks across multiple sectors [14].

## Literature review

Studies have explored the potential to for the pulp and paper industry to reduce energy use and CO<sub>2</sub> emissions through implementation of commercially available technologies for improved energy efficiency and decarbonization. Miller et al. [15] conduct a bandwidth study on industry-wide energy efficiency opportunities for the U.S. pulp and paper sector, finding that currently available best technologies and practices could result in up to 61 % energy savings. Kramer et al. [8] provides a guide for U.S. pulp and paper manufacturers with details on existing energy efficiency technologies and practices and estimated energy savings. Energy intensity of paper production can be reduced by increasing use of recycled paper resources as well as adopting best available technologies; modeling by the International Energy Agency suggests that the sector could reduce energy intensity of production by 1.5 % per year by 2030 to stay in line with a net zero pathway. Improvements to drying processes may have the most efficiency potential, including paper production without water, use of superheated steam, water removal without evaporation, and use of heat pumps to reuse latent heat from drying [16]. Laurijssen, Faaij, and Worrell (2012) conduct energy benchmarking of Dutch paper mills, finding significant opportunities for improved efficiency. Research has also analyzed overall energy and emissions reductions pathways for the pulp and paper industry. Many studies focus on specific countries or regions including the U.S [17], China [18], the European Union [19], Finland and Sweden [20], Brazil [21], Canada [22], Switzerland [23], and Austria [24].

Additional studies assess the potential of emerging technologies. Kong et al. [25] review 25 energy-efficiency technologies in the paper industry at earlier stages of commercialization. Naqvi et al. [12] review research on black liquor gasification, which has the potential to replace recovery boilers for more efficient energy recovery and co-production of other energy products in chemical pulp mills. Zuberi and Hasanbeigi [26] conduct a techno-economic analysis of U.S. industrial heat pump applications, finding that heat pumps have potential applications in the pulp and paper industry and could result in energy and CO<sub>2</sub> savings, though high electricity costs are a barrier to adoption.

Existing research also explores the technical and economic potential of CCS in the pulp and paper industry. Onarheim et al. [27,28] analyze technical and energy performance of amine-based post-combustion CCS in a Kraft pulp mill and an integrated pulp and paper mill, as well as costs under various scenarios for CCS policy incentives. Sagues et al. [13] analyze potential for U.S. pulp and paper mills to adopt bioenergy with CCS. They find that CCS implementation with current federal tax

credits can generate economic returns for some mills, but results are sensitive to mill configuration and proximity to geologic storage. Rosa et al. [29] assess possibilities for bioenergy with CCS in Europe which do not require purpose-grown biomass plantations, including the pulp and paper industry. Results indicate that the pulp and paper industry has the greatest potential for biogenic carbon storage among existing point sources, with technical potential to capture around 62 MT of CO<sub>2</sub> per year. Leeson et al. [30] conduct a techno-economic analysis of CCS in several industrial sectors; pulp and paper was not included in the modeling due to a lack of data, but the authors note that mills are often located near forested areas and far from other industry and transport networks, posing a challenge for CCS operations. Karlsson et al. [31] investigate the implications of CCS in the pulp and paper industry for regional biomass supply in Sweden, finding that competition for biomass logging residues in the energy system (mainly district heating) is a constraint for paper industry BECCS. Ericsson and Nilsson [32] discuss biomass feedstock supply and competition in the context of alternative pathways for pulp and paper decarbonization in the EU. In addition to efficiency, fuel switching, and electrification, the pulp and paper industry can also play a role in decarbonization pathways by transitioning to biorefineries which produce multiple bio-based co-products along with paper, and through utilization of biogenic CO<sub>2</sub> as a feedstock in an overall decarbonized bioeconomy.

## Methods and scenarios

We model the pulp and paper industry within the Global Change Analysis model, a global integrated human-Earth system model that represents the interactions between economic, energy, agricultural, water, and climate systems. GCAM is a recursive dynamic model which represents interactions between several sectors such as land use, water use, energy and the climate. The model operates in five-year time steps from 2015 to 2100 [1].

We add a representation of the pulp and paper industry to GCAM. Fig. 2 below describes our implementation approach. For each region, we model energy use, production, and simple energy technology choice. Technologies are separated into electric processes, process heat, and process heat generated from residue biomass (mainly black liquor) to represent the different levels of competing energy uses within the sector (see SI Fig. 1 for sector structure and technologies represented). Technologies are vintaged to represent the role of capital stock turnover in future energy transition pathways. Note that we only implement CCS for the pulp and paper industry as it pertains to the wood pulp for energy (via black liquor production). There is no CCS implemented for the process heat generated from fossil fuels. Gas or coal with CCS is likely not economic compared to electrifying process heat, whereas biomass with CCS is chosen because it utilizes the existing waste wood product. Note that implementing additional forms of CCS is challenging since paper mills are often located near forested areas and far from other industry and transport networks, posing a challenge for CCS operations [30]. Similarly, the black liquor produced within the pulp and paper industry sector can only be used within that sector and cannot be used by other sectors, since GCAM already produces purpose-grown biomass separately which is used in several sectors. This independent biomass stream is the biomass generated from switchgrass, miscanthus and eucalyptus plantations and second generation biofuels.

We link the use of waste biomass energy recovery with the representation of forest products in GCAM, allowing for endogenous modeling of feedbacks between paper production, forest production, land use, and carbon implications. One major feature of our implementation is that the paper industry is fully coupled with the forest sector of the land module in GCAM. Specifically, the wood pulp commodity from harvested forests is an input into paper production, converted into energy content. We calculate region-specific energy coefficients for each region based on wood pulp production and biomass energy consumption to capture the different availability of biomass

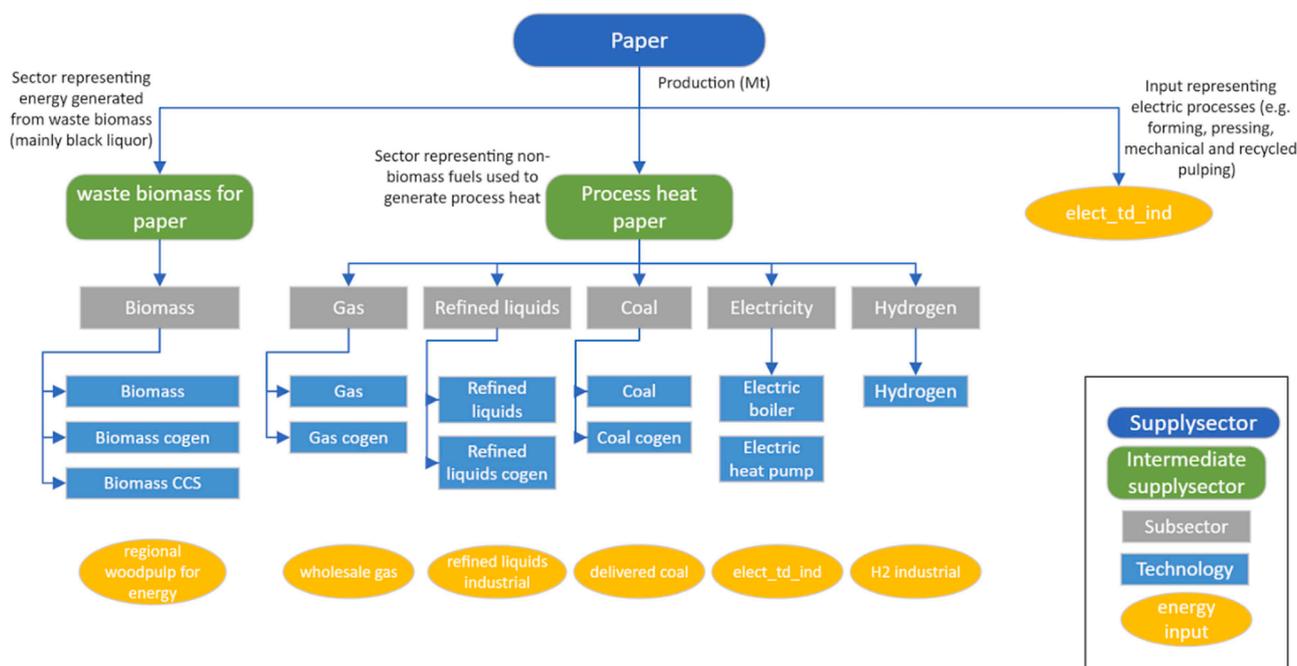


Fig. 2. Paper industry structure implemented in GCAM for this study.

residue, in particular black liquor, based on production practices and availability of raw wood materials. Global trade of forest products (roundwood, sawn wood, and pulp) is also modeled, although we do not include representation of trade of final paper products. We note that pulp production in GCAM represents only chemical pulping as opposed to mechanical pulping. This is because chemical pulping constitutes the vast majority of wood pulp produced globally (75 %). In the US in recent years, nearly 90 % of the wood pulp produced is chemical pulp (as per FAOSTAT production statistics).

Demand for paper products (which is calibrated based on final paper and paper products production data from the FAO) is determined through income elasticity and price elasticity assumptions (See SI Fig. 2 for the relationship between paper demand and income levels). We estimate the relationship between per-capita GDP and paper demand per capita at different income levels based on historical data, although this is a source of uncertainty as patterns of paper consumption will likely continue to change compared to the historical period and may vary across regions.

We model two main scenarios: a reference case (Ref), with no assumed policies and continuation of business-as-usual trends across all sectors; and scenario where the U.S. and all other regions reach net zero CO<sub>2</sub> emissions by 2050 (NZ 2050). Under this scenario, CO<sub>2</sub> is constrained to decline linearly to zero in 2050, with reductions starting between 2020 and 2025. We also include linked carbon pricing for land use change, such that the carbon price for land is 10 % that of the energy sector carbon price. The scenario uses GDP and population growth pathways aligned with the Shared Socioeconomic Pathways (SSP) 2, the “Middle of the Road” scenario [33].

We also run sensitivity analysis to quantify the impact of key variables. We include a scenario where biomass with CCS is not available in the paper sector, to analyze the impact that the negative emissions technology has on paper production and land use. We also run a scenario where CO<sub>2</sub> emissions associated with land use change are not included in the carbon price.

## Results and discussion

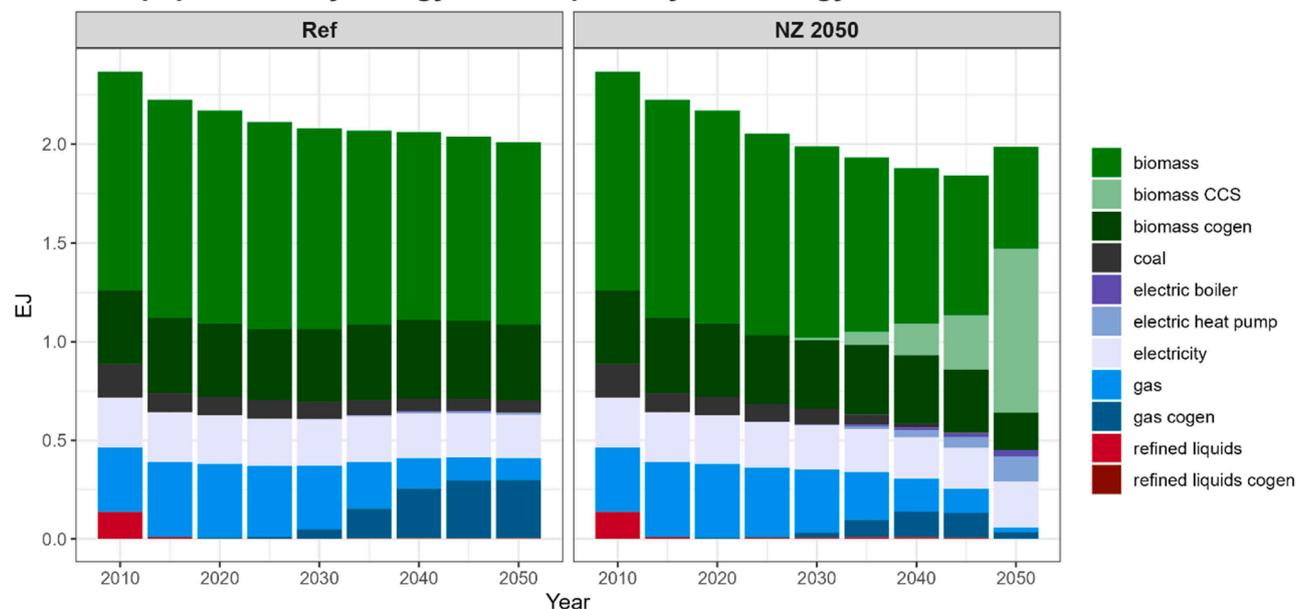
### Paper industry transition pathway

Modeling the pulp and paper industry within a globally consistent, integrated human-Earth system framework indicates that the U.S. paper sector can rapidly reduce CO<sub>2</sub> emissions and reach net-negative emissions just before 2050. The required carbon price schedule to reach net zero emissions is shown in SI Fig. 3.

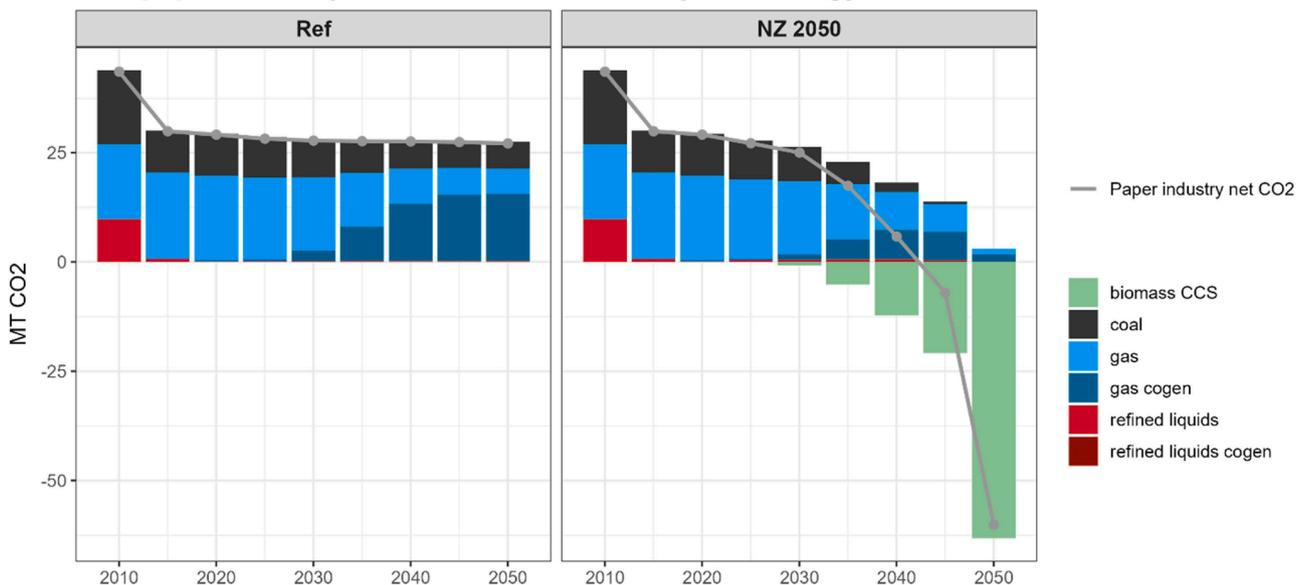
In the reference scenario (Fig. 3 below), CO<sub>2</sub> emissions from the pulp and paper industry plateau between 2020 and 2050, at around 27 MT CO<sub>2</sub> direct emissions per year. In the policy scenario, paper industry emissions decrease by about 14 % between 2020 and 2030. Emissions reductions accelerate after 2030, with emissions reduction of about 75 % between 2030 and 2040. The sector reaches net negative CO<sub>2</sub> emissions (excluding indirect emissions from electricity use and including negative emissions from biomass growth and CO<sub>2</sub> capture) by 2045, slightly earlier than the overall U.S. economy-wide net zero target.

In the net zero scenario (Fig. 3 below), the share of electricity consumption in process heat generation increases from nearly 0 % in 2020 to 9 % in 2050. Industrial heat pumps play a larger role in the electrification of process heat relative to electric boilers, which are less economic due to their lower efficiencies combined with the high price of electricity per unit of energy. While coal still makes up about 4 % of process heat in 2050 in the reference scenario, it is effectively phased out by 2050 in the net zero scenario. The share of natural gas in the net zero scenario decreases from about 20 % in 2020 to about 3 % in 2050 in the net zero scenario; this relatively quick fuel switching reflects the economic competitiveness of industrial heat pumps as a technology option for generating process heat. However, gas use in the paper industry under a net zero scenario is likely to be sensitive to the rate of technological and cost development of electric process heat technologies, such as electric boilers and industrial high-temperature heat pumps, gas and electricity prices, and the rate of equipment turnover and inertia in the existing capital stock. The share of biomass in process heat increases from 75 % (1.45 EJ) in 2020 to 88 % (1.54 EJ) in 2050; the largest increase occurs between 2045 and 2050 due to the high carbon price, which incentivizes additional biomass use with CCS. This effect is sensitive to the extent to which land-use change CO<sub>2</sub> emissions are priced

### A U.S. paper industry energy consumption by technology



### B U.S. paper industry direct CO2 emissions by technology



**Fig. 3.** In energy consumption figure (panel A), electricity indicates existing electric-based processes, while all other technologies are for process heat generation. In CO<sub>2</sub> by technology figure (panel B), both negative and positive emissions from biomass are allocated to final demand sectors, so conventional biomass is treated as carbon neutral. Figure excludes indirect emissions from electricity consumption.

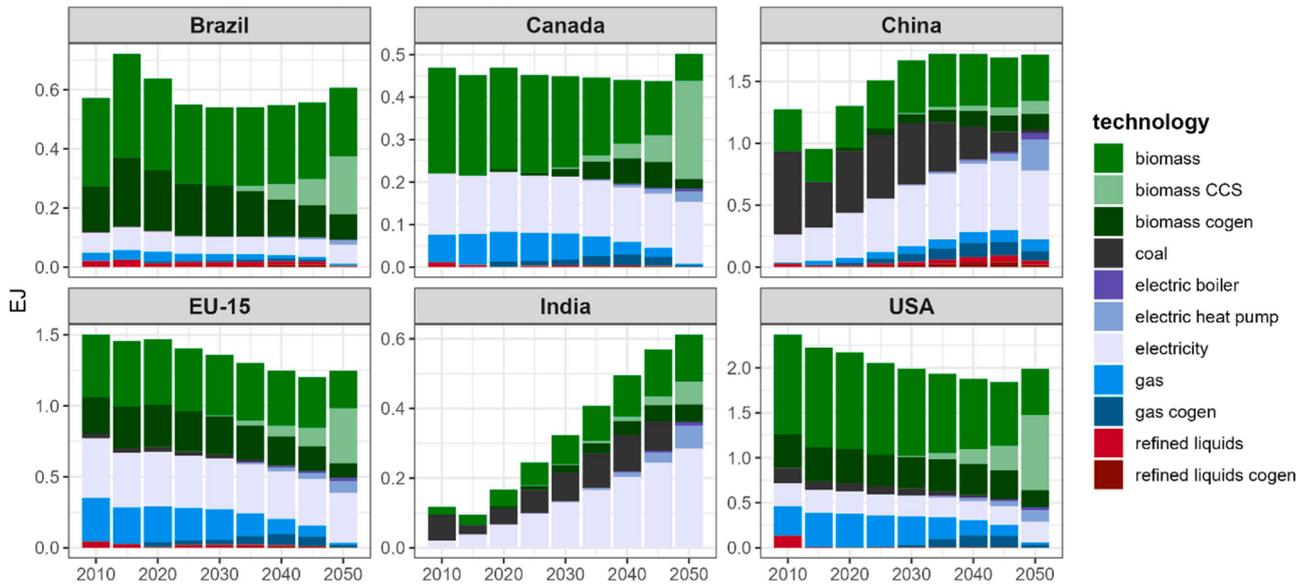
under the carbon tax, which determines how much additional value the sector can generate by sequestering CO<sub>2</sub> relative to the value of land-based carbon sequestration.

U.S. paper production continues its declining trend in the reference scenario (Fig. 5), reflecting the recent historical decline in printing and newsprint paper due to digitalization. Annual paper production is lower in the net zero scenario compared to reference between 2025 and 2045 (about 7 % lower by 2045), due to higher prices of energy and raw materials. However, in 2050, in the net zero scenario, the carbon price increases to drive net CO<sub>2</sub> emissions to zero, which increases the economic incentive to generate negative emissions from biomass with CCS in the paper industry (Fig. 5). As a result, paper production in 2050 rebounds nearly to 2020 levels. This result is seen only in the U.S. and other regions with high forest product availability (Fig. 4), and thus capacity to use black liquor combustion to take advantage of the

additional value stream provided by CCS. Transition pathways vary across regions; regions with more secondary paper production (from recycled paper or imported pulp) and less forested area have lesser capacity to generate energy from waste biomass, and thus are more reliant on electrification of process heat for emission reductions in the paper sector. The trends in paper production are also observed in the effects on prices which decline post 2045 in the US with increasing production (SI Fig. 4)

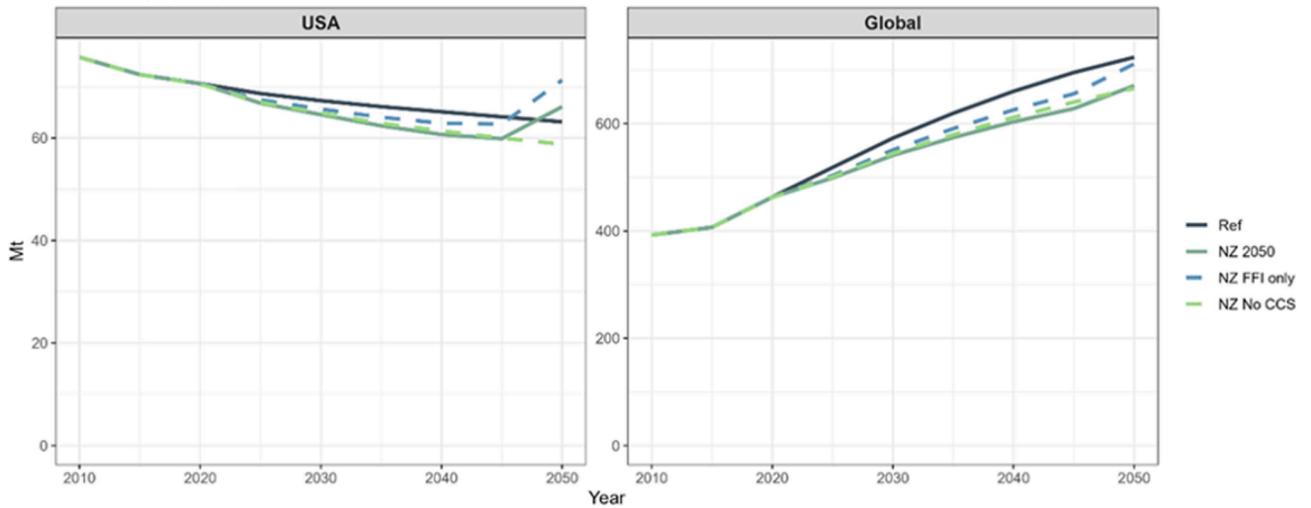
When land use emissions are not included in the carbon price, there is less of a decline in paper production compared to the no-policy reference, as there is no penalty for land-use changes that lead to higher forest product harvesting. Paper industry emissions also decrease more rapidly when land use is not priced, caused by higher use of biomass with CCS; however, upstream emissions from land use change are higher as these are not taxed under the carbon price.

**Paper energy use by technology, net-zero scenario**



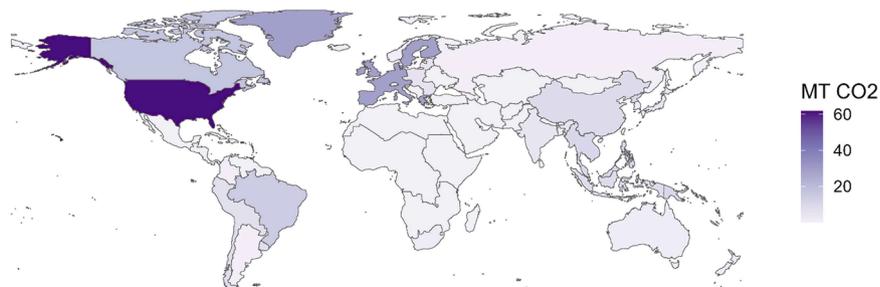
**Fig. 4.** Energy use by source in the paper sector just shown here for the net zero scenario across several regions electricity indicates existing electric-based processes, while all other technologies are for process heat generation.

**Annual paper production**



**Fig. 5.** Annual paper production in the US (left) and the world as a whole (right) across all scenarios.

**Paper industry CO<sub>2</sub> sequestration in 2050, net-zero scenario**



**Fig. 6.** CO<sub>2</sub> sequestration in the pulp and paper industry from biomass CCS, under the net zero scenario in 2050.

Contribution to the overall net zero target

The pulp and paper industry can play a small, but significant role in providing negative CO<sub>2</sub> emissions to contribute to the overall net zero target. In the net zero scenario, the U.S. pulp and paper industry sequesters about 63 MT CO<sub>2</sub> by 2050. The U.S. has the highest CO<sub>2</sub> sequestration in the pulp and paper industry of all GCAM regions (Fig. 6), due to both high paper production and large existing use of biomass combustion from chemical pulping and other residue biomass. Globally, paper industry CO<sub>2</sub> sequestration reaches about 178 MT CO<sub>2</sub> by 2050 in the net zero scenario.

CO<sub>2</sub> sequestration in the paper industry is a relatively small share of total biomass-based technological carbon capture to reach net zero CO<sub>2</sub> emission by 2050. In the U.S. in 2050 under the main net zero scenario, biomass-based carbon sequestration in electricity generation is about 525 MT CO<sub>2</sub> per year; paper industry CO<sub>2</sub> sequestration is about 12 % of that amount. However, CCS adoption in the paper industry can play a significant role in adoption of engineered carbon capture with biomass because of the existing use of waste biomass combustion as part of the paper production process, compared to other forms of negative emissions technologies which rely on purpose-grown biomass with more significant land-use change impacts.

Land-use impacts

The availability of CCS technologies and negative emissions opportunities in the pulp and paper industry under a net zero scenario drives up demand for biomass feedstock. We run a sensitivity analysis to analyze the magnitude of land-use impacts. This scenario includes the same net zero CO<sub>2</sub> constraint but without biomass CCS available in the pulp and paper industry.

Under the reference scenario, overall land allocated to forests increases to about 2.2 million km<sup>2</sup> in 2015 to 2.6 million km<sup>2</sup> in 2050, while the share of managed forests within forest land increases from slightly over half of all forest area in 2015 to about 74 % in 2050 (Fig. 7). In the net zero CO<sub>2</sub> scenario, the carbon price increases continuously over the study period and reaches its highest value in 2050 (Fig. 7). This high carbon price increases the economic benefit of paper production with biomass CCS and drives managed forest land to increase by an additional 270 thousand km<sup>2</sup> in 2050. When CO<sub>2</sub> emissions from land-use change are not included in the carbon price, the additional managed forest land is 317 thousand km<sup>2</sup> higher in 2050 compared to the reference case. Relatedly, unmanaged forest land allocation is 11.5 thousand km<sup>2</sup> and 95 km<sup>2</sup> lower than the reference case in 2050, respectively, in the main net zero scenario and sensitivity scenario with no land use carbon pricing. These land-use impacts are driven solely by increased production of paper with CCS, as we compare these results with the sensitivity scenario with no paper CCS available. With no paper industry BECCS, there is a minimal effect on managed forest land by 2050, and unmanaged forest land increases slightly compared to the reference case. SI Fig. 5 shows the global effects of the net zero scenario on forest cover.

These results highlight a risk of large-scale availability of biomass with CCS and policy supporting deployment of the technology. If carbon removal is the only consideration without proper monitoring of upstream land use impacts, this can incentivize more land conversion from unmanaged to managed forests, resulting in associated loss of forest carbon storage. In the scenario with no paper CCS available, land-use carbon storage is higher, highlighting the tradeoff between technological carbon storage and land-based storage. Previous research on forest carbon storage has demonstrated the value of unmanaged and protected forest land for both carbon storage and biodiversity protection [34]. In

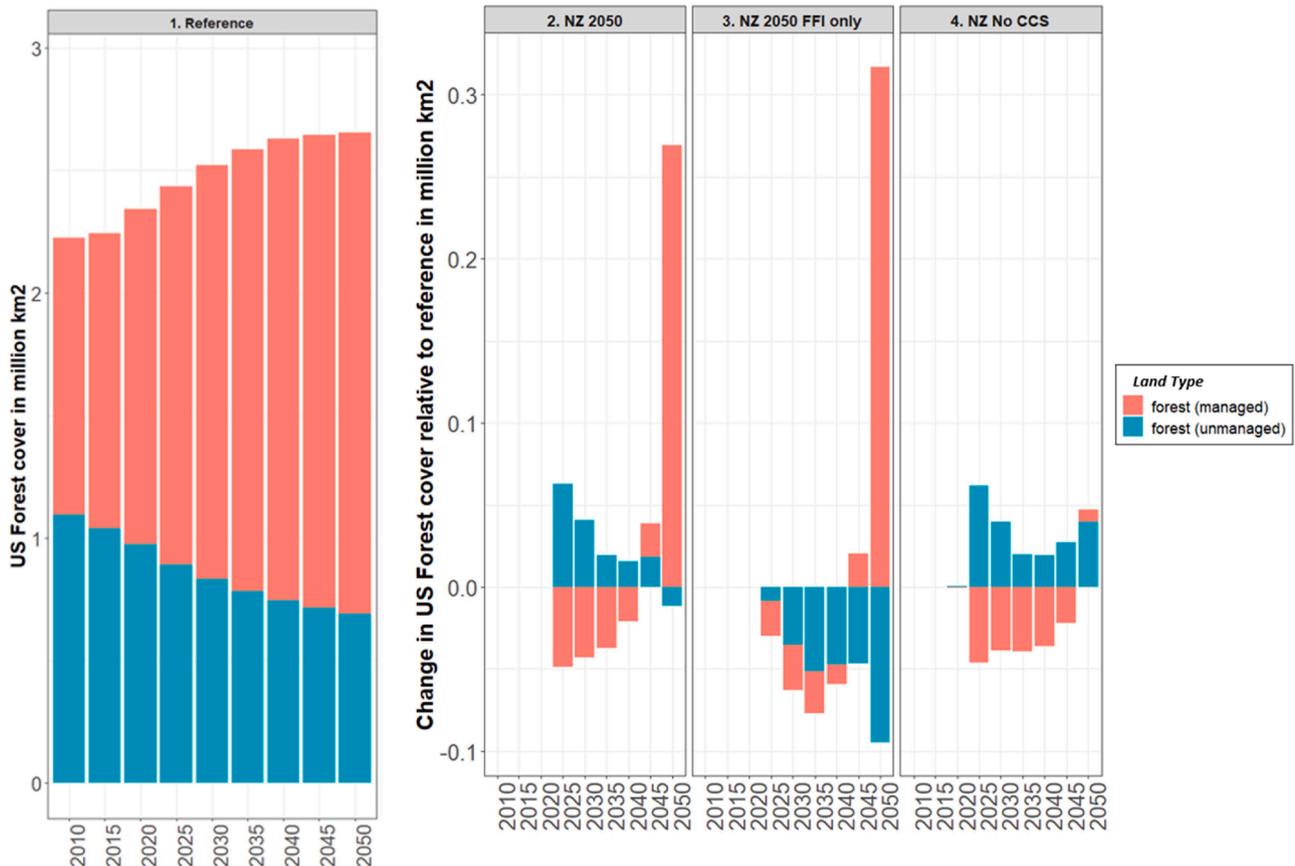


Fig. 7. U.S. forest land allocation and distribution between managed and unmanaged in the reference case, and differences from the reference case in the net zero scenario and sensitivity scenarios.

addition, numerous studies have pointed to the environmental tradeoffs associated with land-use impacts of bioenergy production, including potential loss of biodiversity and ecosystem services [35,36,37,38].

Nevertheless, the existing use of large-scale biomass combustion represents an opportunity for the industry to contribute negative emissions toward reaching climate neutrality through CCS installation deployed with existing waste biomass combustion, without the need for additional purpose-grown biomass. Policy support will be necessary to make CCS financially feasible. However, climate mitigation efforts in the industry should consider these tradeoffs and account for the need to incentivize CCS without driving increased raw material use and land conversion.

### Limitations

There are several sources of uncertainty and modeling limitations in these results. Data on costs and efficiency of emerging technologies including CCS and industrial heat pumps is limited, and there is uncertainty around how these parameters might develop in the future. In addition, the global structure of the model can capture heterogeneity in industry structure between regions, but not at the individual mill level. We develop a set of globally consistent technology cost and efficiency assumptions and include representation of the aggregate paper industry in each region. However, individual mills will vary in their technology options available, including suitability for CCS deployment, depending on factors including capacity, layout, types of products, and purity of CO<sub>2</sub> streams. This is especially important to acknowledge since the net zero scenarios implemented in this manuscript rely on carbon removals from CCS technologies significantly.

While the specific scenario modeled here is informative for analyzing potential impacts on the paper industry and managed forests at different levels of carbon pricing, the significant increase in the carbon price in 2050 is unlikely to be a realistic policy in the real world.

This version of the pulp and paper model implementation also does not include recycling, which impacts industrial energy use as recycled pulping is much less energy-intensive and increased recycling rates can lower overall demand for paper. However, some research has indicated that paper recycling is unlikely to significantly reduce emissions from the sector and paper can only be recycled a limited number of times. Due to data limitations, we do not separately model production of recycled paper.

Finally, future demand pathways for paper products are uncertain. Income elasticity of demand may continue to shift with future developments in digitalization and consumption patterns, as has already been seen with changes in newsprint and packaging demand. The potential development of bio-based and paper-based products to substitute for plastics and petrochemicals introduces an additional source of uncertainty. Future work may explore interactions between the paper and chemical industries in climate mitigation pathways. In addition, as the paper industry is modeled independently of other industrial sectors, we do not have the capacity to explore potential synergies such as the development of biorefineries to produce multiple co-products from biomass, including alternative utilization pathways for black liquor and other residues.

While we find that a net zero scenario implemented in the US in context of the pulp and paper industry would lead to important feedbacks to the forest cover, it is important to note that GCAM is subject to certain limitations with respect to forest modeling especially. GCAM currently only models net land use change (i.e. for e.g. net increase/decrease in forests, net increase/decrease in cropland) [1]. This means that as more forests are harvested, the changes to the soil carbon pool are based on net land use change and may not capture changes to the soil carbon pool based on different harvesting regimes [39].

### Conclusions

These modeling results indicate that comprehensive decarbonization can present an opportunity for the U.S. pulp and paper industry. High reliance on stationary waste biomass combustion in the U.S. and other regions presents an opportunity for the industry to generate additional value through negative CO<sub>2</sub> emissions, provided that policy incentives are sufficient to make deployment cost-effective. At the same time, expansion of biomass energy use with CCS in the paper industry can have implications for the forestry sector and associated land use, carbon sequestration, and biodiversity outcomes.

### CRedit authorship contribution statement

**Molly Charles:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kanishka B. Narayan:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jae Edmonds:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Sha Yu:** Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2024.100160.

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