Report 331
June 2018

The economic and emissions benefits of engineered wood products in a low-carbon future

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GLOBAL CHANGE

JUNE 2018

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Abstract: There has been rapid growth in the use of engineered wood products in the construction sector in recent decades. We evaluate the economy-wide impacts of replacing carbon-intensive construction inputs, such as steel and cement, with lumber products in the US under an emissions constraint. We find that the ability to substitute lumber-based building materials increases production from the lumber and forestry sectors and decreases production from carbon-intensive sectors such as cement. Under a carbon cap-and-trade policy, the ability to substitute lumber products lowers the carbon price and the GDP cost of meeting the carbon cap, with more overall emissions abatement in the construction industry.

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1. Introduction

Climate change is a growing threat to the US economy and the world. There is general agreement that atmospheric concentrations of greenhouse gases (GHGs) must be stabilized. International agreements have called for stabilization such that the global temperature rise from preindustrial levels remains well below 2°C, with an aim of possibly keeping the increase below 1.5°C. Stabilization of atmospheric concentrations of GHGs will require that emissions eventually achieve net zero. With regard to controlling emissions, much attention has been focused on the electricity and transportation sectors of the economy as these are the biggest greenhouse gas-emitting sectors. However, with the need to achieve net zero emissions, attention must be focused on all sectors. Cement and steel, which are primarily used as building materials, are among the most difficult emissions to reduce. One possible alternative is to substitute away from these materials toward wood and engineered wood products, which are less GHG-intensive.

As background, there has been rapid advance in the development of engineered wood products and growth of their use in the construction sector in recent decades. In Europe, cross-laminated timber (CLT), laminated veneer lumber (LVL), glued laminated (glulam) wood, and wood fiber insulation boards (WFIB) experienced annual growth rates between 2.5% to 15% (Hildebrandt *et al.*, 2017). Rising use of engineered wood products is driven by the adoption of new regulations and superior physical, environmental and economic properties for these products compared to mineral-based building materials (Hildebrandt *et al.*, 2017).

Studies have shown that (1) glulam beams have superior performance characteristics and result in fewer carbon dioxide (CO_2) emissions than steel beams (Hassan *et al.*, 2018); (2) buildings with wood frames result in fewer CO_2 emissions than buildings with reinforced concrete materials (Sathre and Gustavsson, 2009); and (3) the central production of prefabricated products reduces costs relative to conventional building techniques (Brandner *et al.*, 2016).

The use of CLT—a wood panel product made by gluing layers of solid-sawn lumber together stacked at 90-degree angles—is predicted to grow rapidly in the future (Brandner *et al.*, 2016; Hildebrandt *et al.*, 2017). CLT was originally developed in Europe but there is now growing research, development, and use in many other countries, including Canada, the US, Japan, China and New Zealand (Brandner *et al.*, 2016). CLT allows the construction of high-rise timber buildings and has been used in the construction of the world's tallest timber buildings (Brandner *et al.*, 2016). CLT-constructed buildings include 'The Tall Wood Residence' (53 meters) at the University of British Columbia, Canada, and 'The Tree' (49 meters) in Bergen, Norway (Mills, 2017). Sumitomo Forestry is planning to build a 350 meter tall, 70-story skyscraper made of 90% wood in Tokyo, Japan (Ellyatt, 2018).

Although many studies emphasize the CO_2 benefits of engineered wood products, to our knowledge, few studies have examined the economic and emission impacts of these products under a climate policy. Sathre and Gustavsson (2007), who show that a carbon tax increases the competitiveness of wood construction materials, is a notable exception.

In this paper, we evaluate the economic and emissions impacts of replacing CO_2-intensive building materials (e.g., steel and concrete) with lumber products in the US under a climate policy. Our analysis develops and deploys an economy-wide model that includes a detailed representation of energy production and use and represents, among other sectors, production of construction, forestry, lumber, and mineral-based construction inputs. The model allows us to evaluate how increased use of lumber products will impact (1) sectoral production across the US economy; and (2) macroeconomic variables, such as the carbon price, the GDP costs of meeting emission goals, and the level of electricity generation.

This paper has four further sections. Section 2 describes the structure and data sources for our economy-wide model and the scenarios implemented in our analysis. Our results are presented and discussed in Section 3. Section 4 concludes.

2. Methods

2.1 Modeling Framework

Our analysis develops a bespoke US-focused, multisector applied general equilibrium model of economic activity, energy, and CO_2 emissions from the combustion of fossil fuels. The model links the US to the rest of the world via sectoral imports and exports and sectors are interconnected by purchases of intermediate inputs. Crucial model features for the analysis of the impacts of using more lumber products in the construction sector are outlined below. Additional information about the model is provided in Appendix A.

The model represents 26 production sectors, listed in **Table 1**, plus investment, household consumption, and government consumption. The model includes 12 sectors related to energy extraction, production and distribution, including seven electricity generation technologies. Key construction inputs represented in the model include non-metallic minerals (e.g., cement, lime and concrete), iron and steel (e.g., pig iron and steel ingots), non-ferrous metals (e.g., aluminum, copper and zinc), fabricated metal products (e.g., fabricated steel), and lumber products (including engineered wood products such as CLT). These sectors are referred to as 'construction inputs' or 'building materials' in the remainder of this paper.

The model also represents forestry, a key input for the production of lumber products, and agriculture, which competes with the forestry sector for land. Paper and paper products, and chemical rubber and plastic products are energy-intensive sectors that are not used intensively by the construction industry. Remaining manufacturing sectors are grouped into either the food processing or other manufacturing sectors. Aggregate sectors are included, separately, for transportation and services.

In each sector, there is a representative firm that produces output by hiring primary factors/inputs and purchasing intermediate inputs from other firms. Production in each sector is represented by a multi-level nest of constant elasticity of substitution (CES) functions. Production by the construction sector is discussed below and production functions for remaining sectors are outlined in Appendix A.

Table 1. Sectors represented in the model

Energy extraction, production & distribution	
`cru`	Crude oil extraction
`oil`	Refined oil products
`col`	Coal extraction
`gas`	Natural gas extraction and distribution
`ecoa`	Coal electricity
`egas`	Gas electricity
`eoil`	Oil electricity
`enuc`	Nuclear electricity
`ehyd`	Hydroelectricity
`ewin`	Wind electricity
`esol`	Solar electricity
`tnd`	Electricity transmission and distribution
Agriculture and forestry	
`agr`	Agriculture
`for`	Forestry
Construction & construction inputs	
`cns`	Construction
`lum`	Lumber
`nmm`	Non-metallic minerals
`i_s`	Iron and steel
`nfm`	Non-ferrous metals
`fmp`	Fabricated metal products
Other manufacturing and services	
`ppp`	Paper and paper products
`crp`	Chemical, rubber & plastic products
`food`	Food processing
`manf`	Other manufacturing
`trn`	Transportation
`ser`	Services

A novel feature of the model is the nesting structure for the construction sector, which is sketched in **Figure 1**. The top level of the production nest assembles composites for (1) building materials, (2) energy-capital-labor, and (3) other intermediates in a Leontief/fixed proportions nest (i.e., the elasticity of substitution between these composite inputs is zero). Within the building materials composite, governed by the elasticity parameter σ_{BM} , producers can substitute between lumber products and other building materials, which are combined in a Leontief nest. If lumber products are less CO_2 intensive than other building materials (as we show below) and $\sigma_{BM} > 0$, this production structure allows the construction sector to abate emissions by using more lumber products in place of other building materials. The construction sector, like other sectors, can also abate emissions by using energy more efficiently (substituting between aggregate energy and the capital-labor composite) and substituting among fossil fuels.

There is little empirical evidence to guide the assignment of σ_{BM}. As noted by Gustavsson *et al.* (2006, p. 1118): '… in applied interfuel econometrics work focusing on micro-data, the research interest so far has been much more on energy substitution than on material substitution issues, so that empirical evidence on material substitution elasticities is still rare.' To estimate the impacts of more lumber use in construction, in our core case, we compare scenarios where $\sigma_{BM} = 0$ (i.e., no substitution among construction inputs) and σ_{BM}= 5. We also consider alternative values for σ_{BM} ranging from 0.5 to 25 in a sensitivity analysis.

The model allows conversion of agricultural land to forest land and vice versa based on economic incentives using a constant elasticity of transformation function. Consequently, more forestry output can be increased in the model by using more land for forestry production (extensification) and/or using forest land more efficiently/increasing yields (intensification). CO_2 emissions from land use and land use change are not considered in the model.

The model is calibrated using the Global Trade Analysis Project (GTAP) Power Database (Peters, 2016) and solved using the Mathematical Programming Subsystem for General Equilibrium (MPSGE) (Rutherford, 1995). Elasticity values in production (except for σ_{BM}) and consumption that, in tandem with input cost shares, govern substitution possibilities are guided by those used in the MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005; Chen *et al.*, 2016).

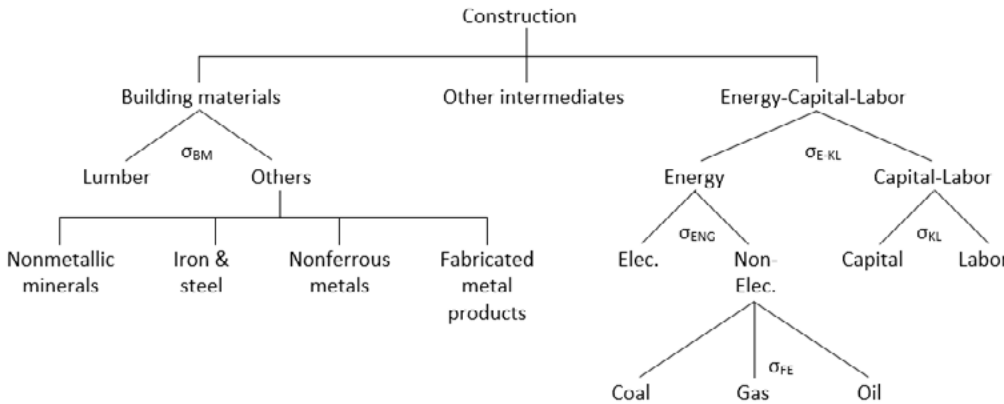

Figure 1. Production nest for construction

Note: Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero.

Table 2. Scenarios

Name	Description
Benchmark	The US economy as represented by the benchmark data in 2011
BAU	The US in 2030 under ‘Business as usual’ (no climate policies)
ETS-NoSub	ETS to meet the US 2030 NDC pledge without substitution among building materials
ETS-Sub	ETS to meet the US 2030 NDC pledge with substitution among building materials

2.2 Sectoral emission intensities

To compare the CO_2-intentsity of different construction inputs, we calculate CO_2 emissions embodied in a dollar’s worth of production of each good. Following Rutherford and Babiker (1997), total embodied emissions are calculated as the sum of direct and indirect emissions. In each sector, direct emissions result from the combustion of fossil fuels in that sector (e.g., coal used by the iron and steel sector), and indirect emissions arise from fossil fuels used by intermediate inputs used by that sector (e.g., coal used to produce electricity that is used as an input for iron and steel production). Formally, total embodied emissions per dollar of output from sector i, E_i are calculated as:

$$E_i = \sum_f D_{fi} + \sum_j E_i \alpha_{ij} \tag{1}$$

where D_{fi} is direct emissions from the burning of fossil fuel f (coal, oil, gas) by industry i per dollar of output, and α_{ij} is the quantity of inputs from sector j used per dollar of output of industry i. Applying equation (1) to each sector results in a system of i equations and i unknowns. After assigning values for D_{fi}, and α_{ij} the system of equation is solved simultaneously to determine values for each E_i.

2.3 Scenarios

The four scenarios examined in our analysis are summarized in **Table 2**. The first, *Benchmark*, requires no simulation and simply reports economic, energy and emission outcomes for the US in 2011, as measured by the database used to calibrate the model. Remaining scenarios simulate outcomes for 2030. Our BAU simulation creates projections for economic, energy and GHG emission outcomes in the US in 2030 under a hypothetical ‘no climate policy’ or ‘business as usual’ case. Key inputs for our BAU simulation include (1) the assignment of technology specific factor endowments for certain electricity sectors, (2) changes in fossil fuel prices, (3) autonomous energy efficiency improvements, (4) autonomous improvements in non-combustion GHG intensities, and (5) improvements in total factor productivity.

Our assignments for technology specific factors for electricity generation types, which drive output from these technologies, are informed by ‘Reference case projections for electricity capacity and generation by fuel (2015–50)’ from EIA (2017). Fossil fuel price forecasts are also guided by EIA (2017). Guided by historical trends and assumptions in the MIT EPPA model (Paltsev *et al.*, 2005; Chen *et al.*, 2016), in all sectors except electricity, we impose autonomous energy efficiency improvements of 1.5% per year in fossil fuel and electricity use. In the electricity sector, there is 0.3% annual improvement in energy efficiency for fossil fuel use. Total factor productivity improvements are endogenous in the BAU scenario and are determined so that simulated US GDP in 2030 equals that forecast by OECD (2017). In the policy scenarios, total factor productivity is exogenous (and equal to values derived in the BAU scenario) and GDP is endogenous.

The final two scenarios use an economy-wide emissions trading system (ETS) to limit CO_2 emissions to a level consistent with the US emissions-reduction pledge under the Paris Climate Agreement. As our model only includes CO_2 emissions from the combustion of fossil fuels and the US emissions pledge concerns all GHG emissions, following Winchester (2018), we impose the proportional reduction in CO_2 combustion emissions relative to BAU in 2030 at 34.3%—consistent with the US Paris pledge estimated by Jacoby *et al.* (2017).

In the *ETS-NoSub* and *ETS-Sub* scenarios, we simulate an ETS that reduces US emissions by 34.3% relative the BAU level, respectively, with and without substitution among construction inputs. Comparing results for the two ETS scenarios facilities estimation of the impacts of using more lumber in construction on economic, energy, and emissions outcomes. In the *BAU* and *ETS-NoSub* scenarios $\sigma_{BM} = 0$, and in the *ETS-Sub* scenario $\sigma_{BM} = 5$. In a sensitivity analysis, in the *ETS-Sub* scenario we consider values for σ_{BM} ranging from 0.5 to 25.

3. Results

3.1 Sectoral emission intensity estimates

Figure 2 reports CO_2 intensities for sectors not classified as energy extraction, production and distribution industries (see Table 1).[1] Total embodied emissions per unit of output—tons (t) of emissions per thousand dollars of output—are decomposed into (1) direct emissions, (2) indirect emissions from electricity use, and (3) emissions associated with other intermediate inputs. Focusing on construction-related sectors, non-metallic minerals (nmm), non-ferrous metals (nfm), and iron and steel (i_s) have relatively high CO_2 intensities. Fabricated metal product (fmp) is moderately emissions intensive, and the construction (cns) and forestry (frs) sectors have low CO_2 intensities. Comparing CO_2 intensities indicates that the construction industry can abate emissions by using more lumber products in place of other construction inputs.

3.2 Policy scenario results

Macro-level results for each scenario are presented in **Table 3**. In the BAU scenario, US GDP in 2030 is $28,690.3 billion,[2] and CO_2 emissions in the same year are 5,899.8 Mt. Simulating an economy-wide ETS to reduce CO_2 emissions by 34.3% without substitution among construction inputs (*ETS-NoSub*) results in a carbon price of $103.4 per ton of CO_2 (tCO_2. The ETS reduces GDP relative to the BAU by $231.2 billion (0.74%).[3] There are also reductions in total electricity and primary energy use relative to BAU, and changes in the composition of energy production. Notably, electricity generation from wind and solar increase, while electricity from fossil fuels, especially coal, decreases.

Changes in sector output are illustrated in **Figure 3**. In the *ETS-NoSub* scenario, excluding energy extraction, production and distribution sectors (see Table 1), transporta-

1 For comparison, the CO_2 intensity for aggregate electricity, the sector with the highest CO_2 intensity, is 5.9 tons of CO_2 per thousand dollars of output.

2 All values in this paper are reported in 2017 dollars. As the model solves for values in 2011 dollars, we convert these values to 2017 dollars using a GDP price deflator from the Bureau of Economic Analysis.

3 These calculations do not include benefits from avoided climate damages due to reduced emissions.

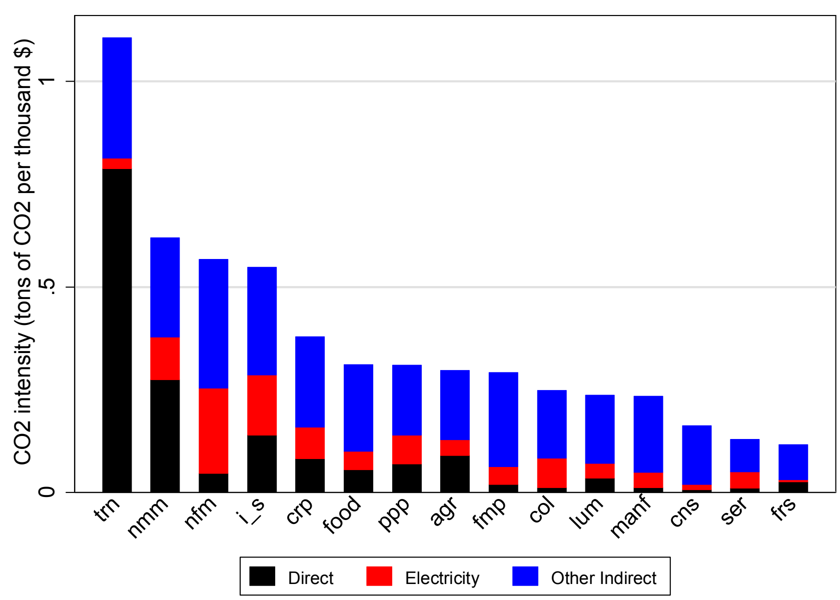

Figure 2. CO_2 intensities for selected sectors. *Note: See Table 1 for definitions of sector abbreviation.*

Table 3. Macro-level results

	2011	2030		
	Benchmark	BAU	ETS-NoSub	ETS-Sub
GDP, \$ b	17,946.6	28,690.3	28,477.1	28,477.5
GDP change relative to BAU, \$ b			-213.21	-212.77
CO_2 emissions, $MtCO_2$	5,107.4	5,899.8	3,876.2	3,876.2
CO_2 price, \$/tCO_2e			103.4	103.2
Electricity, TWh	4,464.5	5,035.7	3,744.9	3,745.7
Primary energy, Mtoe*	2,268.1	2,601.2	2,019.0	2,018.8

Note: * Primary energy from nuclear is based on the amount of heat generated in reactors assuming a 33% conversion efficiency. For wind, solar and hydro, the primary energy equivalent is the physical energy content of electricity generated.

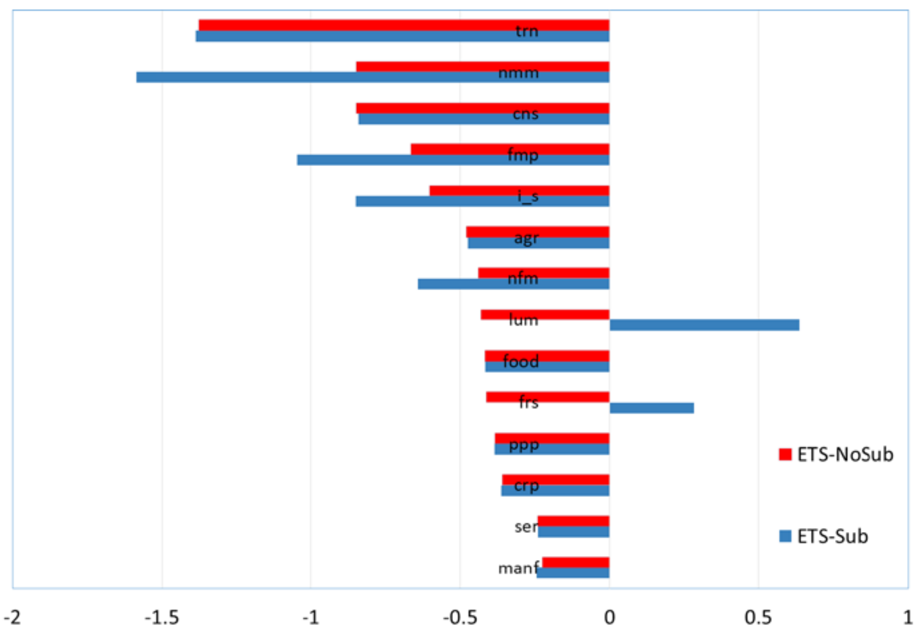

Figure 3. Output changes for selected sectors, %

tion experiences the largest decline in sectoral production (1.4%). There are also relatively large output decreases in the construction sector and some construction input sectors—output of construction (cns), non-metallic minerals (nmm), fabricated metal products (fmp), and iron and steel (i_s) all decrease by more than 0.5% relative to BAU.

Turning to the import composition of the construction inputs, as building materials are used in fixed proportion to output in the *ETS-NoSub* scenario, the percentage change in the use of all construction inputs equals the proportional change in construction output (-0.8% relative to BAU)

In the *ETS-Sub* scenario, relative to BAU, lumber used in the construction industry increases by 2.2% and use of other construction inputs each fall by 2.1%.[4] This additional opportunity to abate emissions results in small improvements in macro-level outcomes. For example, the GDP and cost of meeting the emissions constraint is \$439.6 million lower in the *ETS-Sub* scenario than in the *ETS-NoSub* simulation. Allowing substitution among construction inputs also reduces the carbon price and, by abating more emissions outside the electricity sector, increases electricity production.

At the sectoral level in the *ETS-Sub* scenario, relative to BAU, forestry and lumber production increase by 0.3% and 0.6% respectively, reversing production decreases for these sectors in the *ETS-NoSub* scenario. At the same time, substitution among construction inputs leads to larger declines in construction-input sectors, especially non-metallic minerals. The additional opportunity to abate emissions in the construction sector also results in a small increase in construction output in the *ETS-Sub* scenario relative to the *ETS-NoSub* simulation.

Overall, our results indicate that, under an emissions constraint, allowing substitution between lumber and other

4 When expressed relative to the *ETS-NoSub* scenario, lumber used in construction increases by 3.1%, and use of each other construction input falls by 1.3%.

building materials results in (1) the construction industry using more lumber and less materials with high CO_2 intensities; (2) increased forestry and lumber production and decreased production from CO_2-intensive sectors; and (3) positive macro-level impacts (higher GDP, a lower carbon price, and more electricity production).

3.3 Sensitivity analysis

To evaluate the sensitivity of our findings to the substitution between wood products and other construction inputs, **Table 4** reports results for selected variables for alternative values of σ_{BM} in the ETS-Sub scenario. Results are expressed as changes relative to the *ETS-NoSub* scenario. When $\sigma_{BM} = 5$, the results are identical to those for the core *ETS-Sub* scenario presented in Section 3.2, although most results in that section were reported relative to the BAU scenario.

The results indicate that, at a quantitative level, our findings are robust to alternative values for σ_{BM} and the impacts are larger for higher values of σ_{BM}. That is, for higher values of σ_{BM}, there are larger (1) shifts toward lumber use in the construction industry; (2) changes in sectoral output; and (3) positive macro-wide impacts. When $\sigma_{BM} = 25$ changes in macro variables are relatively small—GDP increases by 0.01%, the carbon price by 0.81%, and electricity generation by 0.09% relative to the *ETS-NoSub* scenario. Changes in construction output are also small, but there are relatively large proportional increases in lumber used in construction (and decreases for other construction inputs) for higher σ_{BM} values. These production inputs shifts drive relatively large changes in output for forestry and construction inputs for larger σ_{BM} values.

4. Conclusions

Given our US economy database, we find that the CO_2-intensity of lumber production is about 20% less than that of fabricated metal products, under 50% that of iron and steel, and under 25% that of cement. This suggests that substitution away from steel and cement toward lumber can be emissions-saving. For our central case, indeed we find that the ability to substitute toward lumber products in construction reduces modestly the carbon price under an economy-wide cap and trade policy and reduces the cost to the economy of the policy by about ½ billion dollars. The potential substitution of wood products and other building materials is fairly uncertain. There are few estimates of this substitution potential in the literature and, given the rapid development of new engineered products that have ever-better structural features, historical evidence on substitution may not be relevant to what is possible in the future. We consider in a sensitivity analysis a wide range of substitution possibilities around our central case. Across this range of substitution options, the GDP savings range from under 0.05 billion to over 2 billion dollars. Given the advances in engineered wood products, its seems likely that the actual substitution potentials may be toward the middle or high end of this range.

It is important to note that our calculations consider only the emissions associated with forestry harvesting and lumber production—that resulting from use of fossil fuels in harvesting, transporting, fabricating and milling lumber products. We do not consider any potential loss of carbon from decaying vegetation material left in the forest during

Table 4. Changes in selected outputs in the *ETS-Sub* scenario for alternative σ_{BM} values relative to the *ETS-NoSub* scenario

	σ_{BM}				
	0.5	**1**	**5**	**10**	**25**
Macro variable changes					
GDP, $ m	50.7	101.2	499.9	984.9	2,348.5
CO_2 price, $/t	-0.02	-0.03	-0.18	-0.35	-0.84
Electricity, TWh	0.07	0.14	0.72	1.41	3.34
Sectoral output changes, %					
Construction	0.00	0.00	0.01	0.01	0.03
Forestry	0.07	0.14	0.70	1.38	3.28
Lumber	0.11	0.22	1.08	2.12	5.04
Non-metallic minerals	-0.07	-0.15	-0.72	-1.42	-3.39
Iron and steel	-0.02	-0.05	-0.24	-0.48	-1.15
Non-ferrous metals	-0.02	-0.04	-0.20	-0.39	-0.94
Fabricated metal products	-0.04	-0.08	-0.38	-0.74	-1.77
Construction input changes, %					
Lumber	0.31	0.62	3.08	6.07	14.44
Other construction inputs	-0.13	-0.27	-1.31	-2.59	-6.16

the harvest, nor any possible loss of soil carbon from disturbance related to harvest. We also do not consider any possible additional benefit of carbon sequestered for long periods in building materials. The change in carbon stored in harvested forest system over time will depend on how the forest is managed. Any harvest of "virgin" forest will almost certainly result in a net release of some carbon, and it can take decades to centuries for such a forest to fully recover. A forest that is regularly harvested will tend to have a lower stock of carbon than a similar forest area that has never been harvested unless management practices significantly enhance growth and productivity (e.g. through fire suppression, fertilization, etc.). Such a forest can likely be managed to maintain a carbon stock while providing a regular timber harvest, and thus have a net zero additional impact on atmospheric carbon stocks. Lumber in buildings ultimately may be abandoned and destroyed, with the carbon finding its way into the atmosphere as a result, and so it does not offer permanent carbon storage. However, to the extent the stock of lumber in buildings increases, and the increase is maintained (even as old buildings are destroyed, new lumber buildings are built), the increase can be a more or less permanent reduction in carbon in the atmosphere.

The source of lumber, and the conditions under which it is grown and harvested, and the fate of wood products deserve further attention to develop a full accounting of the carbon implications of expanded use of wood in building construction. Setting aside those issues, lumber products appear to be advantageous compared with many other building materials, and offer one potential option for reducing emissions from sectors like cement, iron and steel, and fabricated metal products—by reducing the demand for these products themselves.

Acknowledgments

The authors gratefully acknowledge financial support from Weyerhaeuser and the Softwood Lumber Board. The MIT Joint Program on the Science and Policy of Global Change is funded by a consortium of industrial sponsors and Federal grants. For a complete list of sponsors see http://globalchange.mit.edu/sponsors. The findings in this study are solely the opinions of the authors.

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Appendix A. Additional model details

This appendix details production nesting structures for sectors not described in the main text and provides additional detail about the model. All sectors except construction, fossil fuel extraction, electricity production, forestry, and agriculture use the production structure described in **Figure A1**. A key feature of the production nest is substitution between aggregate energy and a capital-labor composite, which allows endogenous improvements in energy efficiency. Other opportunities to abate emissions are provided by the ability to substitute between electricity and (in aggregate) non-electricity energy, and among non-electricity energy inputs (coal, gas, and refined oil). The top-level nest combines non-energy intermediate inputs with the energy-value added composite using a Leontief aggregation.

Mining activities, including fossil fuel extraction sectors, are produced by a CES aggregate of a sector-specific resource (e.g. coal resources for the coal sector) and a composite of capital, labor and intermediate inputs (**Figure A2**).

In fossil-based electricity sectors (**Figure A3a**), there is substitution between fuel inputs and a capital-labor aggregate to capture price-induced improvements in energy conversion efficiency. A key characteristic of non-fossil electricity sectors is the aggregation of a technology specific factor and (aggregated) other inputs in the top level of each production nest (**Figure A3b**). For nuclear electricity and hydroelectricity, which are largely determined by regulations, the top-level elasticity is set equal to zero. This feature allows output for these sectors to be assigned exogenously using estimates from external sources. For other non-fossil electricity sectors (wind, solar, and other electricity), top-level elasticity values capture constraints due to intermittency and resource availability, while at the same time allowing production of these technologies to respond to price changes. To produce supplied electricity (which is purchased by firms and consumers), fossil electricity types and non-fossil electricity outputs are combined using separate CES functions, and the two aggregates are combined using a further CES function (**Figure A3c**). In this nesting structure, non-fossil electricity sources are perfect substitutes for each other, and aggregate fossil fuel electricity is a perfect substitute for non-fossil electricity ($\sigma_{ELE} = \sigma_{NFOS} = \infty$). Aggregate electricity is combined with transmission and distribution in a Leontief nest.

A representative agent derives income from selling factor services and allocates expenditure across private consumption, government consumption, and saving/investment. The nesting structure for final consumption allows substitution among goods with different GHG intensities.

A government sector collects taxes and provides subsidies, and purchases good and services. Net fiscal deficits and, where applicable, revenue from the sale of emission permits are passed to consumers as (implicit) lump sum transfers. Although the model is static, investment is included as a proxy for future consumption and is a fixed proportion of expenditure by each regional household.

Turning to closure, factor prices are endogenous and there is full employment; capital and labor are mobile across sectors (and technology/sector specific resources are immobile); and the current account deficit is a fixed proportion of GDP.

The model is calibrated using the Global Trade Analysis Project (GTAP) Power Database (Peters, 2016). This database augments version 9 of the GTAP Database (Aguiar *et al.*, 2016) and includes economic data and CO_2 emis-

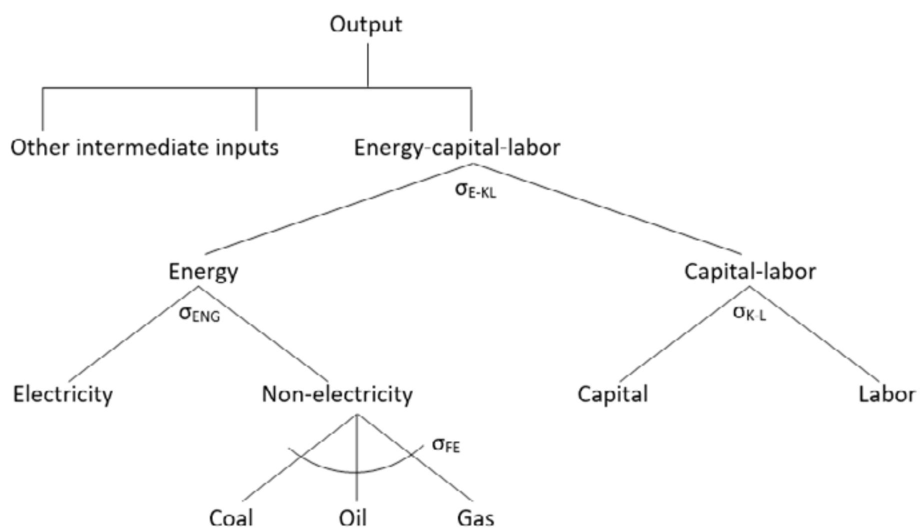


Figure A1. Production nest for all sectors except construction, electricity, mining, forestry, and agriculture

Note: Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero.

sions from the combustion of fossil fuels for 140 regions and 68 sectors. We extract the data for the US and aggregate the sectors to those listed in Table 1 by extending tools provided by Lanz and Rutherford (2016). The base data for the model is a snapshot of the US in 2011.

The model is formulated and solved as a mixed complementarity problem using the Mathematical Programming Subsystem for General Equilibrium (MPSGE) described by Rutherford (1995) and the Generalized Algebraic Modeling System (GAMS) mathematical modeling language (Rosenthal, 2012) with the PATH solver (Dirkse and Ferris, 1995).

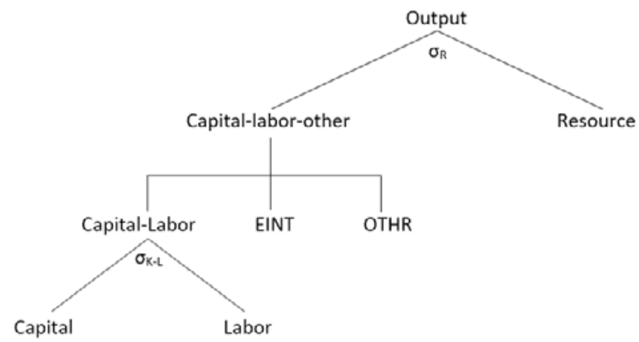
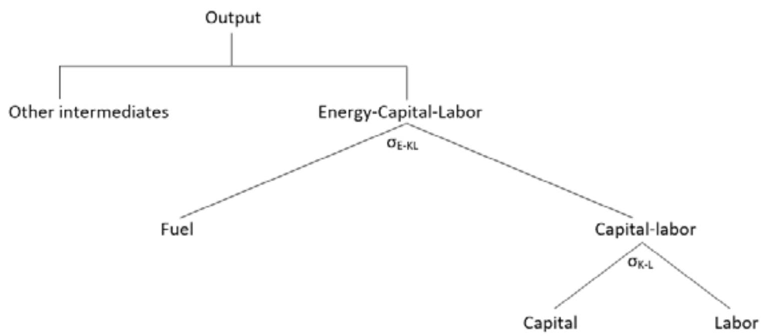
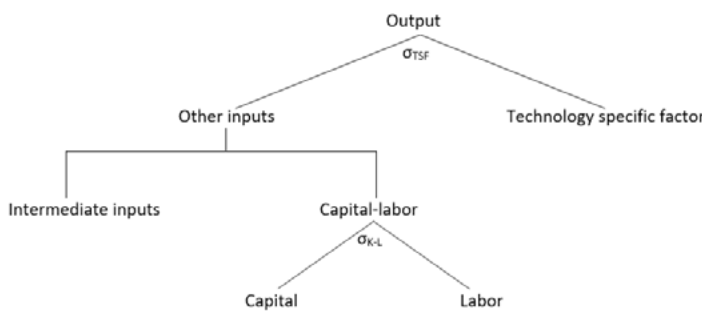


Figure A2. Production nest for mining sectors

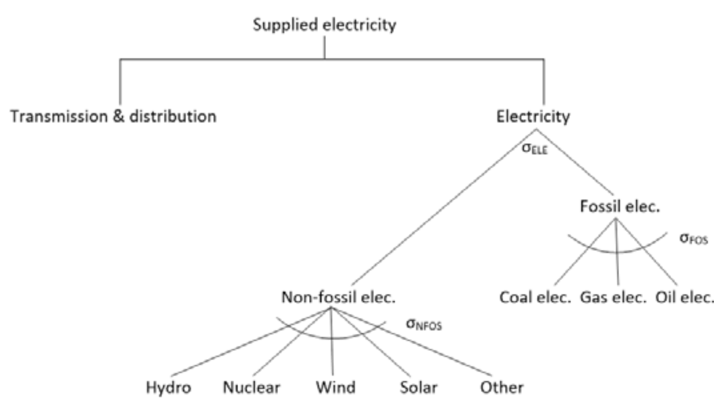
Note: See notes to Figure A1.



(a) Fossil electricity



(b) Non-fossil electricity



(c) Supplied electricity

Figure A3. Production nests for **(a)** fossil electricity, **(b)** non-fossil electricity, and **(c)** supplied electricity

Note: See notes to Figure A1.

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