Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States Using Production-line-based Data and Integration

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Greenhouse gas (GHG) emission levels are causing concern as climate change risks are growing, emphasizing the importance of GHG research for better understanding of emission sources. Previous studies on GHG emissions for the pulp and paper industry have ranged in scope from global to regional to site-specific. This study addresses the present knowledge gap of how GHG emissions vary among paper grades in the US. A cradle-to-gate life cycle carbon analysis for 252 mills in the US was performed by integrating large datasets at the production line level. The results indicated that one metric ton of paper product created a production weighted average of 942 kg of carbon dioxide equivalent (kg CO_2eq) of GHG emissions. Greenhouse gas emissions varied by pulp and paper grade, from 608 kg CO_2eq per metric ton of product to 1978 kg CO_2eq per metric ton of product. Overall, fuels were the greatest contributor to the GHG emissions and should be the focus of emission reduction strategies across pulp and paper grades.

Keywords: Greenhouse gas; Carbon footprint; Cradle to gate; Life cycle assessment

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INTRODUCTION

In 2018, the Intergovernmental Panel on Climate Change (IPCC) published a special report on the impacts of global warming at 1.5 °C above pre-industrial levels, including various greenhouse gas (GHG) reduction pathways and strategies (Masson-Delmotte *et al.* 2018). They predicted that this level of warming will occur by 2040 (Masson-Delmotte *et al.* 2018). At 2 °C above pre-industrial levels, loss in biodiversity and severe flooding risks increase for coastal regions (Masson-Delmotte *et al.* 2018). This mark, however, can still be prevented, making GHG research critical, as it provides a basis for identifying effective GHG reduction strategies.

Industries worldwide are responsible for 21% of global GHG emissions (Fischedick *et al.* 2014). The US pulp and paper industry produced 84.4 million metric tons of products in 2018 (Fisher International 2018). Globally, the paper industry produced approximately 400 million metric tons of products in 2018 and is steadily growing, with increasing production of packaging, tissue, and other specialty grades (RISI 2018).

Previous GHG research on the paper industry mainly falls into two general categories: large-scale studies and life cycle assessments (LCA). Large-scale studies cover global or regional industries and can vary in level of detail reported. For example, the *Fifth Assessment Report of the IPCC* gathered GHG data on global industries and focused on mitigation strategies (Fischedick *et al.* 2014). This report emphasized the GHG reduction potential of energy efficiency improvements in the pulp and paper industry (Fischedick *et al*. 2014). The US Environmental Protection Agency (EPA) has published direct GHG emissions data for all major US industries, including pulp and paper (EPA 2017). This program, the Greenhouse Gas Reporting Program, reported 35.5 million metric tons of CO_2eq from the US pulp and paper industry in 2017 (EPA 2017), which equates to 403 kg CO_2eq per metric ton of product.

Most environmental LCAs focus on a single product, site, or manufacturing line and track the emissions and other environmental impact factors. The purposes of these studies vary and include internal use for production facilities to assess a process or to compare two or more alternative products that are made with different processes or materials. For example, a comparative LCA comparing recycled paper and polystyrene for egg packaging (Zabaniotou and Kassidi 2003) provided carton manufacturers and consumers the ability to make more informed decisions. The American Forest and Paper Association, along with the Forest Products Association of Canada, used an LCA to provide a benchmark for industry (AF&PA 2011). This LCA calculated that one metric ton of coated/uncoated mechanical and wood-free papers generates between 1300 kg CO_2eq and 1600 kg CO_2eq (AF&PA 2011).

Current large-scale studies lack the depth to provide reduction strategies that may apply to different types of mills. Meanwhile, LCAs take great amounts of time and resources to perform, and it is often impractical to cover each mill in the US with traditional LCA methods. To fill the gap, this study sought to better understand the GHG breakdown within the US pulp and paper industry by creating a model based on self-reported mill data and data-mined emission factors (Tomberlin 2019). Using this data, most production lines in the United States (in total, 865 production lines) were assessed. Each product line was separated into one of eleven product categories, and the industry averages and distributions for the individual products were determined. This allowed for more in-depth analysis of noteworthy sources of emissions and areas of focus for emission reductions on an industry-wide product-by-product basis.

EXPERIMENTAL

Scope

The mill data used in this study were sourced from FisherSolve (Fisher International 2018), a global pulp and paper mill database that combines self-reported and data-mined information on the inputs and outputs of mills. This research used 2018 data for operating US pulp and paper mills that reported a finished product. Less than 1% of mills, by production volume, were excluded due to incomplete data. Names of mills were removed for anonymity. Note that the production process, raw material combination, and energy consumption of different types of paper products are different. Such differences were considered by using mill- and production-line-specific process data collected from FisherSolve.

This study follows the ISO standard 14040 series for LCA (ISO, 2006). The system boundary of this study is cradle-to-gate, including wood procurement (from the harvest of logs), the upstream production of other materials such as fuels, electricity, and chemicals, transportation of those materials to mill, and pulp and paper production. GHG emissions generated from all of those activities were tracked and analyzed, with details discussed as follows.

Equations

Three types of GHG were included in this study, CO_2, CH_4, and N_2O, which are major GHG emissions from the pulp and paper industry (Nabinger *et al*. 2019). GHG other than CO_2 were converted to CO_2eq based on their global warming potential (GWP) characterization factors (Eq. 1), based on the latest IPCC report (Myhre *et al*. 2013).

$$kg\ CO_{2eq,\ fossil} = 1(kg\ CO_2) + 30(kg\ CH_{4,\ fossil}) + 265(kg\ N_2O) \quad (1)$$

Equation 2 was used to calculate biogenic CO_2eq emissions from the combustion of biomass; direct oxidation of biomass generating CO_2 was not considered as part of the total GHG emissions. Biogenic CO_2 was separately tracked for each mill because there are some discussions on how it should be accounted for in GWP studies. Some studies have used the carbon-neutral assumption for biogenic CO_2, and thus the characterization factor for the GWP of biogenic CO_2 is zero (Ishikawa *et al*. 2006; Zhang *et al*. 2013). Other studies have indicated the potential impacts of biogenic CO_2 when the dynamics of biomass and climate systems are accounted (Bright *et al*. 2012; Cherubini *et al*. 2012; Levasseur *et al*. 2012; Daystar *et al*. 2017). Biogenic CO_2 was separately tracked herein, so the results can be used by researchers and analysts for future research using different accounting models.

$$kg\ CO_{2eq} = 28(kg\ CH_{4,\ bio}) + 265(kg\ N_2O) \quad (2)$$

Two terms were used to describe GHG emissions in this study: total GHG emissions (kg CO_2eq) and GHG intensity (GHGI, kg CO_2eq / metric ton of product). Total GHG emissions included CO_2eq from all sources (Eq. 3), while GHGI also included all sources of CO_2eq but per metric ton of product (Eq. 4),

$$GHG_{total} = \Sigma\, EFi \quad (3)$$

$$GHGI = GHG_{total} / P \quad (4)$$

where i is an input (kg, J, or W·h) of a mill, EFi is the respective input's emission factor (kg CO_2eq per input unit), and P is the total annual product production (metric tons / year). If the input is a fuel, the emission factor includes both on-site and embodied GHG emissions. If the input is a material (*e.g*., chemicals), the emission factor is for embodied GHG emissions, *i.e*., cradle-to-gate emissions.

Standards

Pulp and paper products were grouped according to the TAPPI TIP 0404-36 (2013) reference, Table 1. The abbreviations will be used in all tables and figures.

Emission Factors

Emission factors were derived from many sources to best fit the system boundary of this study. There were 120 emission factors documented (Tables 2 to 6), and most were given in units of kg CO_2eq per unit (kg, J, or W·h) or converted into the needed unit as required. Electricity emission factors were collected from the EPA's eGRID database based on each mill's state (EPA 2016). Note that such emission factors were only used for electricity purchased from the grid.

Table 1. Paper Product Categories with Abbreviations and Definitions (TAPPI TIP 0404-36 2013)

Category Name	Abbreviation	Definition
Uncoated ground wood	UCGW	Product made with mechanically separated fibers
Coated ground wood	CGW	Coated product made with mechanically separated fibers
Uncoated wood free	UCWF	Chemically pulped paper without coating
Coated wood free	CWF	Chemically pulped paper with coating
Packing paper	PP	Kraft papers used for packing, bleached or unbleached, and including papers with machine-glaze finishes
Bleached paperboard	BPB	Paperboard with a bleached furnish
Unbleached paperboard	UBPB	Paperboard made with virgin fibers, without a bleached furnish
Recycled paperboard	RPB	Paperboard made with recovered fibers
Tissue	Tissue	Lightweight paper mostly used for sanitary products
Market pulp	MP	All pulps produced to be sold
Others	Others	Specialty papers that do not fit into any other category

The emissions associated with electricity generated on-site were calculated based on the emission factors of specific fuels (shown in Table 2) and mill-level fuel consumption data collected from FisherSolve (Fisher International 2018). Emission factors for the various modes of transport (Table 5) were used with the Bureau of Transportation Statistics and the U.S. Census Bureau's *2012 Commodity Flow Survey* estimated distances for each input that was shipped to the mill site (BTS and U.S. Census Bureau 2015) as shown in Table 6. Ideally, the emission factors of electricity and transportation could be differentiated at the mill level by tracking individual source of electricity and transportation activities. However, such analysis is extremely challenging given the highly complex and integrated electricity grid and transportation networks.

Table 2 documents the GHG emission factors for fuels used by the U.S. pulp and paper industry in 2018. Combustion emission factors include GHG emissions generated from burning fuels. For each fuel, the pre-combustion emission factor includes the total GHG emissions generated from raw material extraction, fuel production, and transportation to the mills (in other words, cradle-to-gate GHG emissions). Fuels that are wastes or internally generated (*e.g.*, pulping liquor, railroad ties, and sludge) are assumed to be burden free, therefore their pre-combustion emission factors are zero. In addition, the emission factors of steam were only collected for the steam purchased from outside sources as shown in Table 2. The GHG emissions of steam generated on-site (*e.g.*, through combined heat and power) were calculated based on the fuel consumption collected from FisherSolve and emission factors of specific fuels (that were used to generate steam) in Table 2.

Table 4 lists the cradle to gate GHG emission factors of chemicals used in the U.S. pulp and paper industry. The chemical type (first column) indicates the specific unit process where each chemical is used. For example, chlorine is used in pulp bleaching, thus the chemical type is marked as bleaching in Table 4.

Table 2. GHG Emission Factors for Fuels Used by the US Pulp and Paper Industry in 2018 (EPA 2018)

Fuel	Pre-combustion Emission Factor (kg CO_2eq / GJ)	Combustion Emission Factors			
		Carbon Dioxide (kg CO_2 / GJ)	Methane (kg CH_4 / GJ	Nitrous Oxide (kg N_2O / GJ)	Total GHG (kg CO_2eq / GJ)
Biodiesel	0.002	70.0*	1.04×10^{-3}	1.04×10^{-4}	0.06
Biogas	2.890	49.4*	3.03×10^{-3}	5.97×10^{-4}	0.25
Compressed natural gas (CNG)	0.017	50.3	9.48×10^{-4}	9.48×10^{-5}	50.3
Coal	6.120	89.7	1.04×10^{-2}	1.52×10^{-3}	90.4
Natural gas	0.009	50.3	9.48×10^{-4}	9.48×10^{-5}	50.3
Liquefied natural gas (LNG)	0.008	50.3	9.48×10^{-4}	9.48×10^{-5}	50.3
Methanol	0.004	67.9*	0.00	0.00	0.00
Number 2 oil	0.013	70.1	2.84×10^{-3}	5.69×10^{-4}	70.3
Number 6 oil	0.013	71.2	2.84×10^{-3}	5.69×10^{-4}	71.4
Petcoke	0.034	97.1	2.84×10^{-3}	5.69×10^{-4}	97.3
Pulping liquor	0.00	89.1*	1.80×10^{-3}	3.98×10^{-4}	0.16
Railroad ties	0.00	88.9*	6.82×10^{-3}	3.41×10^{-3}	1.11
Refuse-derived fuel (RDF)	0.00	86.0	3.03×10^{-3}	5.97×10^{-4}	86.2
Recycled fuel oil	0.00	70.1	2.84×10^{-3}	5.69×10^{-4}	70.3
Sludge	0.00	88.9*	6.82×10^{-3}	3.41×10^{-3}	1.11
Steam purchases	0.086	62.9	1.18×10^{-3}	1.18×10^{-4}	62.9
Tires	0.00	81.5	3.03×10^{-2}	4.08×10^{-3}	83.4
Waste wood	0.00	88.9*	6.82×10^{-3}	3.41×10^{-3}	1.11

* Biogenic carbon dioxide sources are marked and were excluded from the total GHG emission factor and total annual GHG emissions.

Since this study covers a large number of pulp and paper mills across the United States, not all chemicals listed in Table 4 are used in each individual mill. Instead, Table 4 is a comprehensive list of all chemicals used in pulp and paper mills that have different process configurations, products, and feedstocks.

Table 3. Upstream Emission Factors for Wood Procurement (National Renewable Energy Laboratory 2015)

Wood Type	GHG Emission Factor (kg CO_2eq / kg dry basis)
Northern hardwood chips	0.22
Northern hardwood logs	0.05
Northern softwood chips	0.22
Northern softwood logs	0.05
Northern softwood sawdust	0.12
Southern hardwood chips	0.09

Table 4. Upstream (Cradle-to-gate) GHG Emission Factors for Chemicals Used by the US Pulp and Paper Industry

Chemical Type	Chemical Name	GHG Emission Factor (kg CO_2eq / kg dry basis)	Reference
Bleaching	Chlorine	1.07	Wernet *et al*. (2016)
	Hydrogen peroxide	1.18	
	Methyl alcohol	0.18	
	Oxygen	0.11	
	Ozone	6.52	
	Sodium chlorate	0.40	
	Sodium chloride	0.28	
	Sodium hydrosulfite	3.85	
	Sodium hypochlorite	0.96	
	Sulfuric acid	0.16	
Pulping	Ammonium	2.89	Wernet *et al*. (2016)
	Calcium carbonate	1.45	
	Caustic soda	1.35	
	Lime	1.14	
	Magnesium sulfate	0.24	
	Sodium carbonate	0.52	
	Sodium sulfate	0.51	
	Sodium sulfite	1.50	
	Sodium sulfide	3.04	
	Sulfur	0.23	
Pigment Filler	Clay	0.001	Wernet *et al*. (2016)
	GCC	0.02	
	PCC	0.32	
	Talc	0.01	EPA (1995)
	Titanium dioxide	4.60	Wernet *et al*. (2016)
Pigment Coating	Clay	0.001	Wernet *et al*. (2016)
	GCC	0.02	
	PCC	0.32	
	Synthetic pigments	0.78	National Renewable Energy Labratory (2015)
	Titanium dioxide	4.60	Wernet *et al*. (2016)
Pulping Mineral	Talc	0.01	EPA (1995)
Wet End	Alkaline size	3.50	Triantou (2009)
	Alum	0.57	Wernet *et al*. (2016)
	Retention aid PAM	2.78	
	Rosin size	1.63	
	Wet-end starch	0.97	
Paper Dyes	Dyes	0.78	National Renewable Energy Labratory (2015)
	Dyes, FWA	0.78	
Paper Other	Creping aid	2.06	Wernet *et al*. (2016)
	Dry strength	1.84	
	Wet strength	2.29	
Paper Coating	Coating starch	0.97	Wernet *et al*. (2016)
	Latex	2.62	
	Size press starch	0.97	
Recycling	Deinked chemicals	0.87	Wernet *et al*. (2016)

GCC – ground calcium carbonate; PCC – precipitated calcium carbonate; PAM – polyacrylamide; FWA – fluorescent whitening agents

Table 5. GHG Emission Factors for Transportation Methods (EPA 2018)

Method	GHG Emission Factor (kg CO_2eq / (metric ton · km))
Truck (medium- and heavy-duty)	0.139
Rail	0.016
Water	0.041
Air	0.903

Table 6. Distances and Percent-by-weight Distributions for Transportation of Materials Going to US Pulp and Paper Mills (BTS and U.S. Census Bureau 2015)

Commodity Type	Total Average Distance (km)	Truck (km)	Truck % by Weight	Rail (km)	Rail % by Weight	Water (km)	Water % by Weight	Air (km)	Air % by Weight
Coal	140	93	18%	922	68%	548	6%	0	0%
Fuel oils	50	48	54%	1232	1%	0	0%	0	0%
Other petroleum fuels	158	122	68%	1419	13%	288	12%	0	0%
Chemicals	1065	216	54%	674	26%	562	13%	1034	0.1%
Logs and wood	296	165	98%	1568	2%	0	0%	0	0%
Pulp	420	261	78%	1502	22%	0	0%	0	0%
Waste and scrap	194	240	60%	502	25%	453	14%	0	0%

RESULTS AND DISCUSSION

This study calculated that 79.5 million metric tons of CO_2eq and an additional 104 million metric tons of biogenic CO_2 were emitted from the US pulp and paper industry in 2018. Half of these CO_2eq emissions were from the production and combustion of fuels, with 95% of those fuel GHG emissions being fossil-based and 5% originating from biomass. The EPA calculated direct emissions data, including fuel combustion without biogenic CO_2, from US mills and reported a total of 34 million tons of CO_2eq emissions per year (EPA 2017), which is close to the total GHG emissions from fuel combustion in this study (39.7 million metric tons of CO_2eq in 2018). The total GHG emissions calculated in this study (79.5 million metric tons of CO_2eq) were twice the value reported by the EPA due to the greater system boundary (inclusion of upstream emissions in the production of fuels and other inputs) of this research.

For comparison purposes, the average GHGI weighted by production volume for each product category was calculated, as summarized in Table 7. The Others category had the greatest GHGI (1978 kg CO_2eq / metric ton of product), likely due to products in this category being specialty products, such as bible and grease-proof papers. These papers require more energy to produce, are smaller-scale, and are not co-located with a biomass boiler, as shown in the high amounts of fuel and electricity used, resulting in high GHGI values. Tissue suffers from the same issues and also has a high GHGI value. Low GHGI values were observed for products produced at large scale at one facility, with biomass-derived energy being very prominent.

Table 7. GHGI for all US Pulp and Paper Product Categories

Category	Total Annual Production	GHG Intensity						Biogenic CO_2 Intensity
		Total	Fuel	Electricity Purchases	Wood, Upstream	Chemicals, Upstream	Transportation	
	(million metric tons of product / year)	(kg CO_2eq / metric ton of product)						(kg CO_2 / metric ton of product)
US Total	84.4	942	474	223	97	60	88	1232
UCGW	1.3	608	227	168	114	45	55	271
CGW	1.5	1511	1105	154	77	105	70	864
UCWF	7.4	1148	651	181	115	102	99	1552
CWF	3.0	1057	511	198	130	131	88	1749
BPB	6.9	857	416	85	151	96	109	2131
UBPB	22.5	714	355	111	115	43	89	1515
RPB	18.8	691	421	176	14	25	55	255
PP	2.5	1559	718	567	127	54	93	1313
Tissue	8.4	1720	886	682	39	26	87	344
MP	11.1	855	241	202	186	101	125	2253
Others	1.0	1978	1063	667	60	75	114	785

A considerable amount of biogenic CO_2 is emitted by the pulp and paper industry. A visualization of Table 7 is provided in Fig. 1, showing that, for 5 of 11 categories, biogenic CO_2 emissions exceeded fossil-based GHG emissions. This result was due to the industry's heavy use of bio-based fuels, particularly pulping liquor and waste wood. Together, these two fuels provided 64% of the energy consumption (excluding electricity) of the US pulp and paper industry, as shown in Fig. 2.

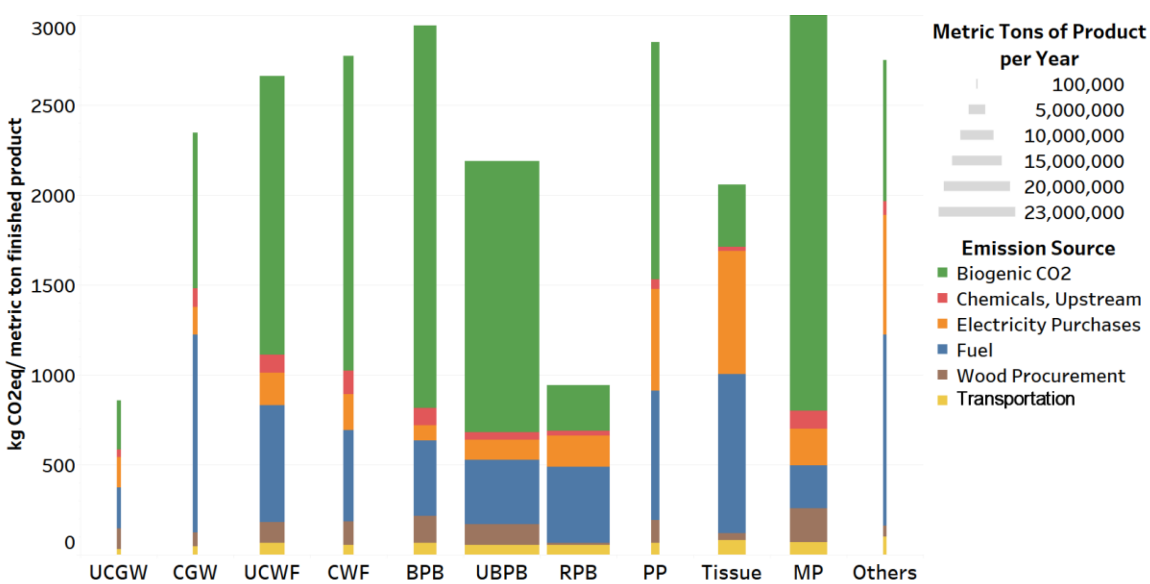

Fig. 1. GHGI sources and biogenic CO_2 comparison for each product category

With the carbon neutrality assumption, these two fuels only account for 1.3% of total GHG emissions. As discussed previously, the emission factors of electricity and transportation were not differentiated at the mill level. However, such uncertainty may not have large impacts on the results for two reasons. First, Fig. 1 shows that transportation counts for only a small percentage (on average 4% across all product categories) of total GHG emissions. Second, GHG emission factors of electricity purchased have already been differentiated at the state level based on the location of each mill, and only two product categories (tissue and others) have significant GHG emissions from electricity purchases (>20%).

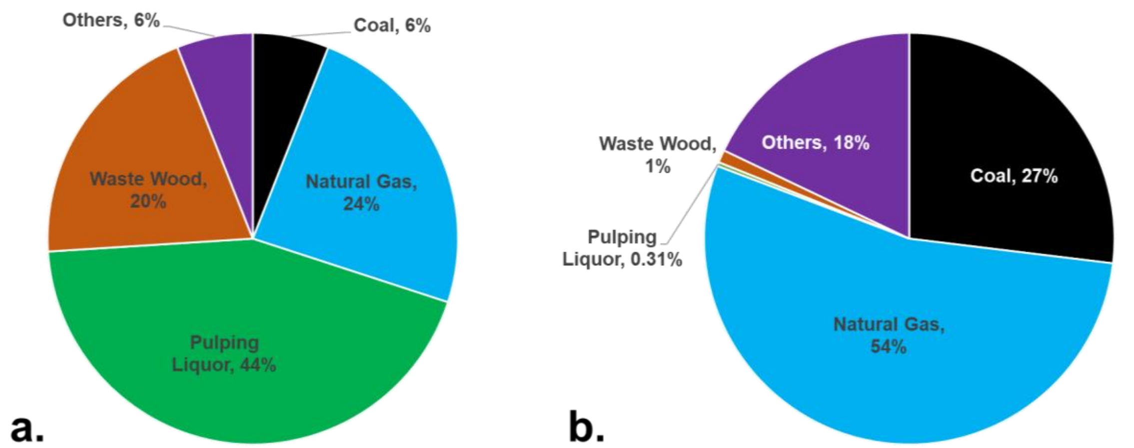

Fig. 2. (a) Energy consumption of the US pulp and paper industry by major fuel types and (b) GHG emissions of the US pulp and paper industry by major fuel types

For each paper category, the greatest contributor to GHG emissions was fuel, even with the heavy reliance on bio-based fuels and the exclusion of biogenic CO_2. Natural gas alone was responsible for 54% of fuel GHG emissions industry-wide, with coal responsible for an additional 27% (Fig. 2). The proportions of fuel types used differed among the paper categories (Fig. 3), though all categories except UCGW mostly relied on coal and natural gas.

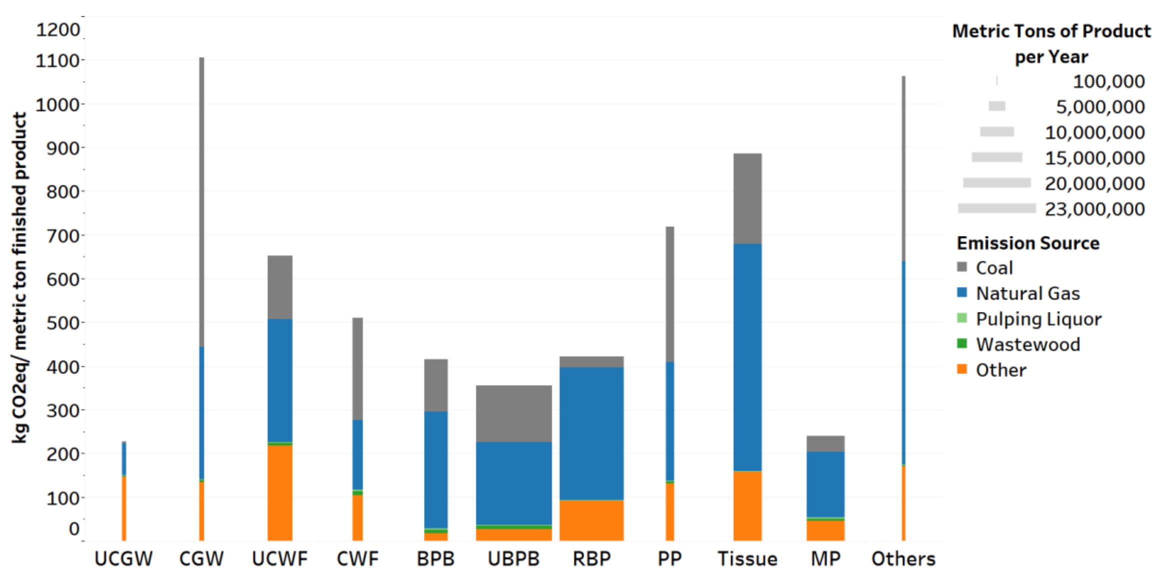

Fig. 3. Fuel GHGI for each paper category broken down by source, excluding biogenic CO_2

Since fuel accounts for 50% of total GHG emissions, excluding biogenic CO_2 for the US pulp and paper industry (Table 8), fuel switching could be a promising strategy for GHG reduction. Figure 4 illustrates the fuels' GHG emissions and costs on a per-heating-unit basis. The cost data were collected from FisherSolve (Fisher International 2018) and uses the average price paid by mills in the US in 2018. With the exceptions of biodiesel and biogas, most bio-based fuels used in 2018 by the pulp and paper industry were less expensive than fossil fuels on a per-heating-unit basis. However, two major bio-based fuels, pulping liquor and sludge, are byproducts/wastes of pulp and paper production and generally not sold in the market. Thus, their availability is subject to mill processes and technology, limiting the potential for fuel switching to these sources.

Table 8. Industry Total GHG Emission Contributors, Excluding Biogenic CO_2

Source	Total GHG Emissions (kg CO_2eq in 2018)	Percentage of Total GHG Emissions (%)
Fuel	3.97×10^{10}	50
Electricity	1.90×10^{10}	24
Wood procurement	7.95×10^{9}	10
Chemicals	4.77×10^{9}	6
Transportation	7.95×10^{9}	10

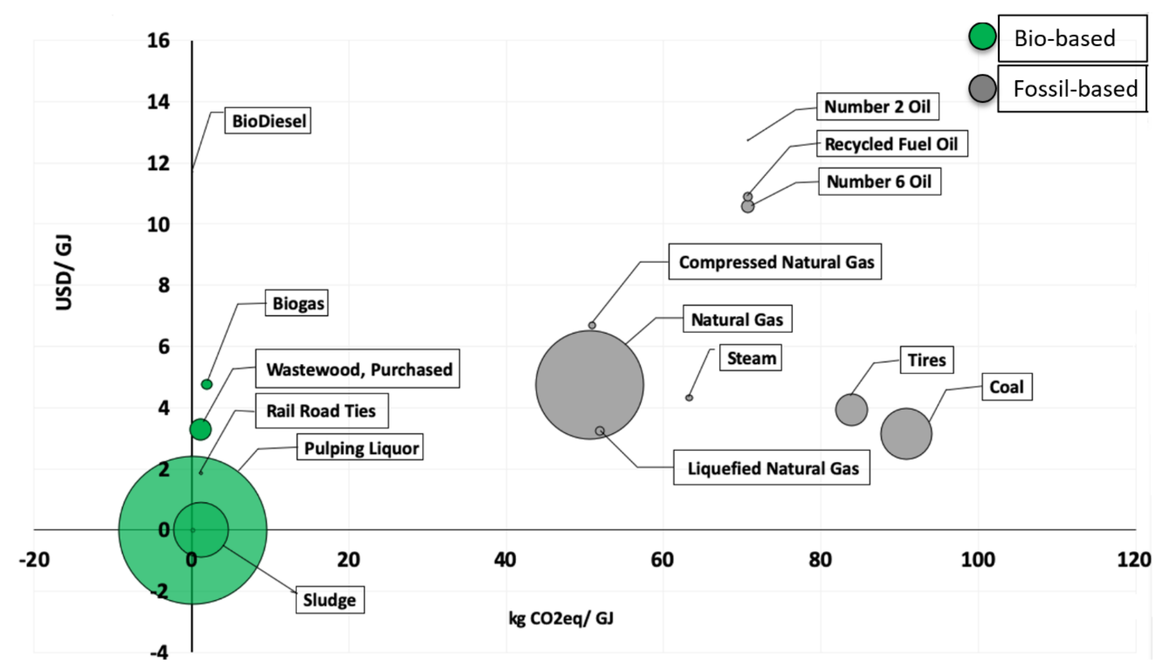

Fig. 4. Emission intensities and cost comparison for various fuels used in the US pulp and paper industry. Bubble size represents the relative use industry-wide.

In addition to the simple fuel-cost considerations, fuel-switching decisions must entail capital cost analyses of purchasing equipment, logistics, and operational issues that occur with using solid fuels relative to fluid fuels. These considerations need to be evaluated on a mill-by-mill basis, given the variability of mill processes and regional resources that exist in the United States. Both techno-economic analysis (TEA) and environmental LCA are powerful tools for mills to explore different fuel-switching options from both economic and environmental perspectives. More research is needed to better understand the tradeoffs of each fuel-switching option and to improve the technical applicability of low-carbon fuels in different pulp and paper production processes.

Emissions related to electricity purchases made up 24% of total GHG emissions by the US pulp and paper industry (Table 8), excluding biogenic CO_2. Tissue had the greatest electricity GHGI, which reflects the high percentage (68%) of mills that only buy pulp rather than producing it. Internal mill electricity production may be considered along with lower-emission fuels to decrease the GHG emissions of a manufacturing site.

Another pathway to reduce energy-related emissions is to improve energy efficiency, as emphasized by many previous studies, such as the *Fifth Assessment Report of the IPCC* (Möllersten *et al*. 2003; Fleiter *et al*. 2012; Myhre *et al*. 2013). For the pulp and paper industry, an energy study conducted by the US Department of Energy estimated an energy savings of 465 TBtu/y (491 PJ/y) nationwide by adopting the state-of-the-art technologies of pulping and papermaking and utility systems in which paper drying and the powerhouse, where steam and electricity are generated on-site, have the greatest energy-saving potential (Miller *et al*. 2015). Another international study indicated great energy-efficiency improvement opportunities by modifying wood digesters and improving steam production and distribution (Tam *et al*. 2009). However, these studies were sector-wide analyses. The implementation of specific technologies is highly mill-specific and will need a thorough investigation of economic feasibility, operating changes, and other potential benefits or disadvantages. More discussions regarding improving energy efficiency and reducing GHG emissions of pulp and paper production appear in Tomberlin (2019).

Fiber sources varied from mill to mill and were the third greatest contributor to the US pulp and paper industry's total GHGI, making up 10% of industry-wide GHG emissions (Table 8), excluding biogenic CO_2. Of the categories studied, RPB had the lowest GHGI from wood procurement, given that RPB is mostly produced from recycled fibers and only a small amount of wood is used to enhance the pulp. This study assigned zero GHG emissions to pulp purchases and recycled fibers to avoid double counting.

The upstream production of chemicals was another source of GHG emissions, composing 6% of total industry GHG emissions in 2018 (Table 8), excluding biogenic CO_2; the emissions were affected by the quantities and types of chemicals. Figure 5 shows GHG emissions broken down by the chemical types used in different processes. In general, the processes with the greatest GHG emissions from chemicals were coating, pulping, and bleaching. As a result, the coated papers (CGW and CWF) had greater chemical GHGIs than their uncoated counterparts (UCGW and UCWF), as shown in the chemical column of Table 7. Similarly, of the paperboard categories, RPB had the lowest chemical GHGI, as it lacks chemical pulping, while BPB had the highest, as it includes pulping and bleaching.

The last GHG contributor examined in this study was the transportation of fuel, wood, recycled fiber, pulp, and chemicals to the mill site. Transportation contributed 10% of the industry's total GHG emissions (Table 8), excluding biogenic CO_2. This emission source had the smallest GHGI range among product categories. Market pulp, however, had the greatest transportation GHGI due to its heavy reliance on wood, which is transported with high moisture content. All other categories had some pulp purchases, which are shipped with a lower moisture content than wood. The high moisture content means that the wood is heavier than recycled materials or pre-made pulp on a per-mass-of-usable-fiber basis, and it requires more fuel for transportation.

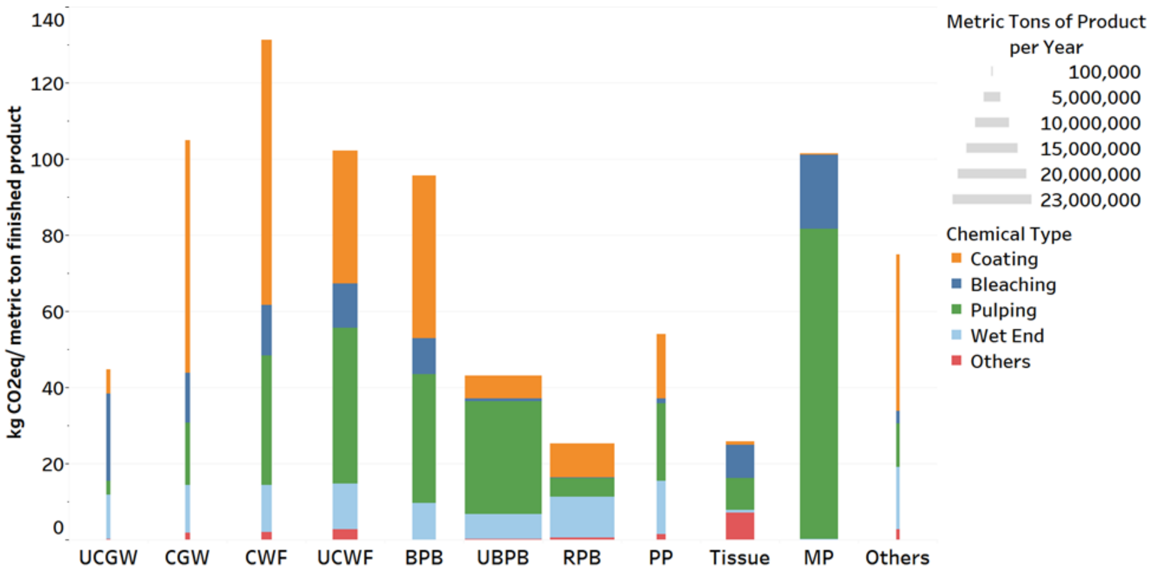

Fig. 5. Chemical GHGIs for each paper category broken down by chemical type. Only upstream emissions from the production of each chemical were included. Table 3 lists the chemicals included in each type.

The above results have been expressed in averages for each product category, but product lines within a category vary. One unique contribution of this study was the investigation of such variations of mills within the same product categories. Table 9 shows the statistical summary for GHGIs of individual mills in the same product category. The variations of GHGI within each product category are very large (as demonstrated by the large differences between minimum and maximum, and large standard deviations, Table 9). However, most of the mills with high GHGI have low production volumes, as show in Fig. 6.

Table 9. Statistical Summary for GHGI of Each Category

Category	Number of Product Lines Represented	Minimum	Maximum	Average*	Standard Deviation
		kg CO_2eq / metric ton of product			
UCGW	16	201	6590	1210	1475
CGW	14	292	29920	3403	7386
UCWF	128	134	85630	2630	7967
CWF	29	319	12800	1763	2593
BPB	37	276	20190	1479	3144
UBPB	55	293	3247	814	452
RPB	157	83	3778	3412	609
PP	76	537	44180	3963	6984
Tissue	228	115	33800	2799	5268
MP	86	421	20800	1931	3412
Others	39	794	89820	7848	16820

*The average in this table is arithmetic mean (not production weighted average).

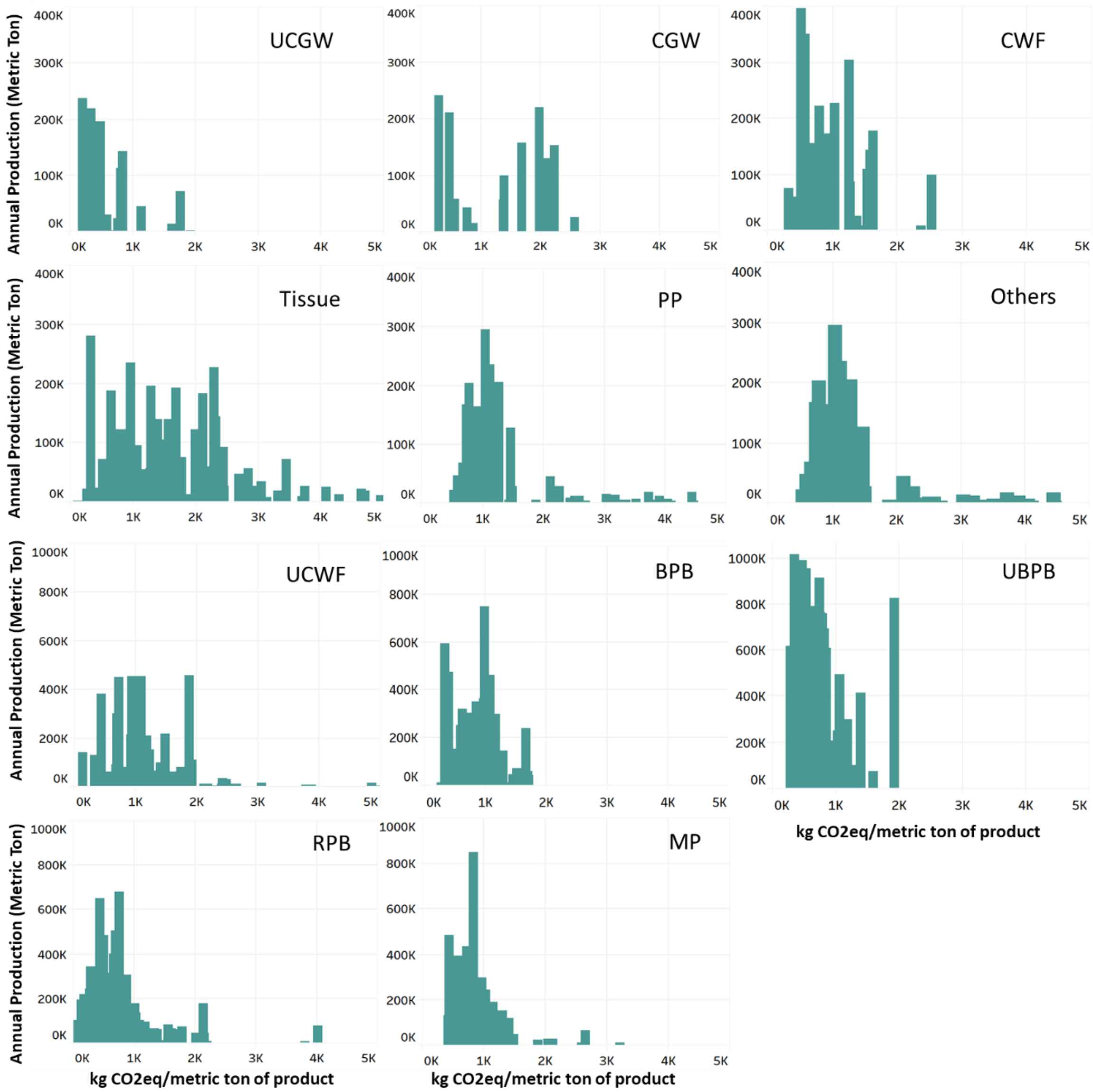

Fig. 6. GHGI distributions for each product category by production. Data over 5000 kg CO_2eq / metric ton of product were excluded for figure readability and they make up less than 5% of data points and total production. K = 1000.

GHGI values larger than 5000 kg CO_2/metric ton of product were excluded in Fig. 6, as those mills contributed to less than 5% of total production of each product category and were considered as outliers. Those outliers significantly raised the arithmetic mean and standard deviation of each category (shown as average in Table 9), but their impacts were highly diluted when production volume is considered (which is why the weighted averages shown in Table 7 are much smaller than the arithmetic means in Table 9).

In general, Fig. 6 shows that product categories with smaller production volume (UCGW, CGW, CWF, Tissue, PP, Others, production < 400,000 metric ton/year) have wider distributions than product categories with larger production volume (UCWF, BPB, UBPB, RPB, MP, production >400,000 metric ton/year). This could be due to wider varieties of product types, production methods, and fuel compositions for smaller mills, those mills may have more opportunities for GHG emission reductions. For larger mills, there may be less room for GHG emission reductions that may exist with products that have high tails or high outliers.

CONCLUSIONS

1. From cradle to gate, the production volume weighted average metric ton of pulp and paper product in the US produced 942 kg CO_2eq.
2. The source breakdown of total GHG emissions of the US pulp and paper industry was as follows: fuels 50%, electricity 24%, wood procurement 10%, transportation 10%, and chemicals 6%.
3. The GHGI varied greatly between and within paper categories due to differences in production methods and energy-use structures.
4. Distributions showing GHGI variances within product categories revealed some categories having much smaller spreads (CGW, CWF, BPB, and UBPB) than others (Tissue, PP, and MP). Wider spreads were likely due to varieties of production methods, fuel compositions, and products within each category.
5. More biogenic CO_2 was emitted by the US pulp and paper industry than all other GHG emissions combined.

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