On-Site Energy Consumption and Selected Emissions at Softwood Sawmills in the Southwestern United States

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Abstract

Presently there is a lack of information describing US southwestern energy consumption and emissions generated from the sawmilling industry. This article uses a mail survey of softwood sawmills in the states of Arizona, Colorado, and New Mexico to develop a profile of on-site energy consumption and selected emissions for the industry. Energy consumption is categorized by fuel type on a production basis for both renewable and nonrenewable sources for production year 2012. Selected emissions from on-site energy consumption were also estimated for respondent sawmills. Survey respondents represented 35 percent of total softwood lumber production of 169.2 million board feet. Total annual on-site sawmill energy required was 64.8 billion British thermal units. Sixty-one percent was derived from diesel fuel, primarily for on-site rolling stock; 35 percent was from electricity; 3 percent was from gasoline used for on-site rolling stock; and the remainder was from propane and wood. Energy produced from nonrenewable sources accounted for 94 percent of total on-site energy consumption. Off-site electricity generation for consumption at sawmills comprise the majority of all emissions in this analysis: 62 percent of CO_2, 99 percent of CH_4, 94 percent of NO_X, 99 percent of SO_X, and 99 percent of particulate matter $\leq$ 10 μm (PM_{10}). Diesel fuel, which supplies the majority of on-site energy, comprises 36 percent CO_2, 0 percent CH_4, 5 percent NO_X, 0.4 percent SO_X, and 1.1 percent of PM_{10}.

Debate continues as to which types of energy sources are considered carbon neutral (Searchinger 2010, Cherubini et al. 2011, Lippke et al. 2012, Schulze et al. 2012, Miner et al. 2014). However, carbon dioxide has long been recognized as a heat-trapping gas (Callendar 1949). Although the impacts and solutions for global climate change are debated, the continued extraction and combustion of otherwise permanently sequestered fossil carbon has been clearly identified as a significant contributor to increasing atmospheric carbon dioxide concentrations (Solomon et al. 2009, Oliver et al. 2014). The use of renewable energy such as solar, wind, hydroelectric, and biomass not only increases domestic energy production, it also decreases fossil carbon emitted to the earth's atmosphere (Jones et al. 2010, Puettman and Lippke 2012, Loeffler and Anderson 2014). Also, Tilman et al. (2009) noted that sustainably harvested wood and forest residues not only have very low carbon impacts, but can substantially displace fossil fuels. As a result, increasing renewable energy production has become a major objective in the United States as evidenced in the Biomass Research and Development Act of 2000, the Energy Policy Act of 2005, and the Paris Agreement of 2015.

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This paper was received for publication in October 2015. Article no. 15-00060.

Forest Prod. J. 66(5/6):326–337.
doi:10.13073/FPJ-D-15-00060

In this context, the sawmilling sector of the wood products industry contributes significantly to achieving renewable energy targets. In 2010, sawmills were responsible for slightly less than half of the total wood products industry energy demand in the United States, consuming 232 trillion British thermal units (Btu; US Energy Information Administration [EIA] 2013). A significant portion of total energy demand at sawmills is derived from renewable energy sources, mostly primary processing residue from mill operations with some slash from logging operations (hereafter referred to as biomass) that is used as fuel for process heat and power (US Department of Energy [DOE] 2011). Of the 1,931 trillion Btu of wood energy consumed in the United States in 2009, 211 trillion Btu was consumed by sawmills for lumber production (EIA 2011, 2012). In 2007 the US Environmental Protection Agency (EPA) estimated that greater than 65 percent of total wood product manufacturing energy requirements was met by wood bioenergy, and in 2013 the American Wood Council (AWC) estimated that 58 percent of the energy requirement for softwood lumber production came from wood bioenergy (EPA 2007, AWC 2013).

In the western United States, which has the largest softwood lumber–producing capacity in the country (Spelter et al. 2009), the forest products industry has undergone substantial changes since 2002, particularly in the southwestern states of Arizona, Colorado, and New Mexico. During 2002, 282.3 million board feet (MMBF) Scribner were harvested from forestlands in these states, and in 2012 harvest was 182.3 MMBF (Morgan et al. 2006, Sorenson et al. 2016). Additionally, the number of sawmills declined from 82 to 62 during that time, and sawmill production capacity declined from 470 to 348 MMBF/yr. The origin of harvested timber also shifted significantly. In 2002 the majority of timber harvested was from private and tribal timberland, whereas in 2012 approximately 75 percent of harvested timber came from lands managed by the US Forest Service (Sorenson et al. 2016). Considering the recent changes in the wood products industry in these three states, together with increasing recognition of the benefits of renewable energy, it is important that the industry, policymakers, and the public are aware of this industry's energy requirements, carbon footprint, and potential for expanding renewable energy usage to displace fossil fuels (Database of State Incentives for Renewables & Efficiency 2016).

There are many reasons why accurate data describing the energy consumption and emissions associated with the sawmill industry in the southwestern United States are needed. In 2012, a total of 3,550 trillion Btu of primary energy was consumed in the southwestern states of Arizona, Colorado, and New Mexico, or about 3.7 percent of total US energy (EIA 2015a). The vast majority of energy produced and consumed in these three states is derived from fossil sources, except that Arizona has substantial nuclear power generating capacity. Only 7.8 percent of total energy consumption was produced from renewable sources in the three states (EIA 2015a). In regions outside the Southwest, the wood products industry is both a major producer and consumer of renewable energy (Loeffler et al. 2016). In contrast, a significant portion of the industry's energy needs in the Southwest are met by nonrenewable sources. On the basis of scale, energy intensity, and generation of biomass by-products, the wood products industry in the Southwest is a logical area in which to develop new bioenergy capacity (EIA 2015b).

A basic understanding of current energy requirements for sawmill operations in the Southwest is lacking, as are data describing the emissions generated by the industry during production of sawn products. There is no available information describing the current status of Southwest sawmills' energy consumption and emissions at scales that can adequately inform decision making and public policy. Although firm-level audits of energy consumption at sawmills are often conducted to guide internal decision making, results are typically proprietary, and rarely aggregated in ways that make industry-level information available to the public, policymakers, and other stakeholders. Furthermore, results are representative of specific mill operations and do not account for efficiency and operational variations among sawmills. Because the structure and productivity of wood products industries varies from region to region, simply applying or extrapolating national- or regional-level energy estimates to other regions is not appropriate.

Objectives

Presently there is a lack of information describing southwestern energy consumption and emissions generated from the sawmilling industry. Analysis at this scale is most important to regional and state policymakers, especially in areas where the wood products industry has experienced significant change. Specifically, empirical energy consumption data and high-resolution profiles of energy use and emissions are needed to identify opportunities for energy efficiency gains, industrial bioenergy expansion, and potential fossil fuel displacement in the sawmill industry. In addition, generating estimates of emissions associated with the industry provides baseline information from which analysis of emissions reductions or displacement can occur through expanded renewable energy production.

In this effort, we begin to address these knowledge gaps by providing aggregated energy consumption and selected emissions data and analysis for sawmills in the southwestern states of Arizona, Colorado, and New Mexico using a survey of 2012 operations. It is worth noting that 2012 lumber production in the three states was about 68 percent of 2002 production (Sorenson et al. 2016), and this represents substantial upheaval in the industry. Given that 20 sawmills have closed since 2002 in a region with low sawmill capacity compared with its forested area, the sawmills that remain in production have weathered the deep market downturn of the Great Recession of 2007 to 2009, and are under market pressure to remain competitive in national and global markets, especially by reducing costs and increasing efficiency (Woodall et al. 2012). Moreover, national and state policies demand that more energy derived from renewable sources be utilized to displace fossil fuels and reduce additions to atmospheric carbon and greenhouse gas concentrations. Aggregating energy consumption at this level is detailed enough to allow individual firms to gauge energy efficiency relative to their competitors, yet broad enough to afford policymakers a solid basis for decision making by characterizing an economically important manufacturing industry at the state and sector levels.

Methods

This study focused on the sawmill industry of the wood product manufacturing sector in the southwestern states of Arizona, Colorado, and New Mexico, and generally follows the methods of Loeffler et al. (2016). To address the knowledge gaps that exist between regional and national energy and emissions assessments, and to better understand fuels, energy needs, and emissions associated with sawmills, we compiled energy consumption information for sawmills operating in these states during calendar year 2012. This year was selected because detailed sawmill production data were being collected by the authors in conjunction with another research effort (Sorenson et al. 2016). Energy consumption is quantified by fuel type and renewable or nonrenewable designation, and presented in units of both total energy consumption and per unit production. Selected emissions are presented in total emissions, per unit production, and potentially avoided fossil fuel emissions. We further present results in light of production trends in the industry.

Study area

The geographic boundaries for this analysis are the states of Arizona, Colorado, and New Mexico (Fig. 1). Ranging in elevation from 70 to 13,161 feet, the forests of Arizona and New Mexico are dominated by primarily pinyon-juniper (*Juniperus* spp., *Pinus edulis,* and *Pinus monophylla*), ponderosa pine (*Pinus ponderosa*), woodland hardwoods, and to a much lesser extent the dry mixed conifer forest type, which is composed primarily of Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), white pine (*Pinus monticola*), and blue spruce (*Picea pungens*). Ranging in elevation from 3,315 to 14,413 feet and at higher latitude, Colorado generally has more diverse forest ecosystems. Pinyon-juniper dominates lower elevations and comprises the majority of forestland in the state; the fir–spruce–mountain hemlock (*Abies* spp., *Picea* spp., and *Tsuga mertensiana*) vegetation group is the second-most common type by area; and the aspen-birch (*Populus tremuloides* and *Betula* spp.) group also has significant acreage in Colorado. To a lesser yet still significant extent, hardwoods, lodgepole pine (*Pinus contorta*), ponderosa pine, and Douglas-fir are present throughout Colorado. Across all ownerships, these states have a combined total of 66.3 million acres of forestland, with Arizona containing 18.6 million acres, Colorado containing 22.9 million acres, and New Mexico containing 24.8 million acres. Of this amount, the US Forest Service manages approximately 26.7 million acres, or 35 percent of total forestland in the three states. Four million acres of these Forest Service lands are reserved and timber harvesting is prohibited on reserved lands (US Department of Agriculture [USDA] 2013).

Working with university and state cooperators, the US Forest Service has monitored the sawmilling industry in Arizona, Colorado, and New Mexico since at least 1967 (Wilson and Spencer 1967, Setzer and Wilson 1970). In these states the number of forest products mills, employment, volume of timber harvested, timber processing capacity, and volume of lumber produced has declined substantially from historical highs in the 1960s and 1980s (Hayes et al. 2012, Sorenson et al. 2016). Despite the decline, the industry has remained an important outlet for woody material produced by public, private, and tribal forestland owners and managers. Whether management goals are to reduce the risk and impacts of wildfire, generate revenue, or restore functioning ecosystems, sawmills continue to be the leading purchasers and users of timber harvested, accounting for 65 to 80 percent of the timber harvested or processed in the three states. However, other timber products, particularly industrial fuelwood, have increased as a proportion of the total harvest volume (Sorenson et al. 2016). As sawmilling infrastructure has declined, management activities have increasingly focused on removing smaller-diameter trees for forest restoration and fire hazard reduction (Reynolds et al. 2013). In 2012 there were 110 wood product manufacturers in the three states that converted timber into lumber, house logs, post and poles, vigas and latillas (i.e., roof and ceiling timbers), log furniture, pellets, animal bedding, and fuelwood. Sixty-one of these facilities were sawmills, which employed 475 people (Bureau of Labor Statistics 2015, Sorenson et al. 2016).

Survey

Statewide censuses of timber processing facilities are periodically conducted as part of a national effort to collect and report timber products output (TPO) information for the US Forest Service Forest Inventory and Analysis Program. The censuses are intended to collect and report utilization of timber harvest, quantify primary forest products firms operating at the time of the census and their sources of raw material, and quantify the outputs and sales values of finished products and residues (Sorenson et al. 2016). In 2013 an energy questionnaire was designed to coincide with the TPO census of timber processors in Arizona, Colorado, and New Mexico for calendar year 2012 activities to collect sawmill energy consumption information for the same year. The questionnaire collected information about each sawmill's 2012 energy consumption by energy source using a series of open-ended questions grouped in three distinct sections: fuel for equipment, nonelectric heat and steam, and electricity. Mailing was paired with follow-up phone calls to increase participation in the survey.

The questionnaire asked specifically for consumption of diesel, gasoline, and propane for on-site rolling stock; consumption of wood/hog fuel, natural gas, heating oil, and propane for thermal needs, including both heat and steam; and consumption of electricity, including grid power and on-site generation (e.g., a stand-alone generator), with associated consumption of wood/hog fuel, natural gas, diesel, gasoline, and propane for on-site power generation. In all cases, ''other'' and ''other fuel'' options were provided, with space for description, and the questionnaire also included a question asking for a description of any on-site biomass system that was operational but not used in 2012. For grid electricity, each respondent's electricity provider was identified, and this information was used to determine the proportion of each sawmill's grid electricity generated from different sources on the basis of the electricity provider's portfolio. Portfolios in this region include variable combinations of power from nuclear, natural gas, coal, solar, wind, and hydro. Clarification of questionnaire responses was made using follow-up phone interviews. As previously discussed, the sawmill industry has enough facilities in this region to protect proprietary data for individual firms, ensure an adequate number of responses, and produce results that are comparable with

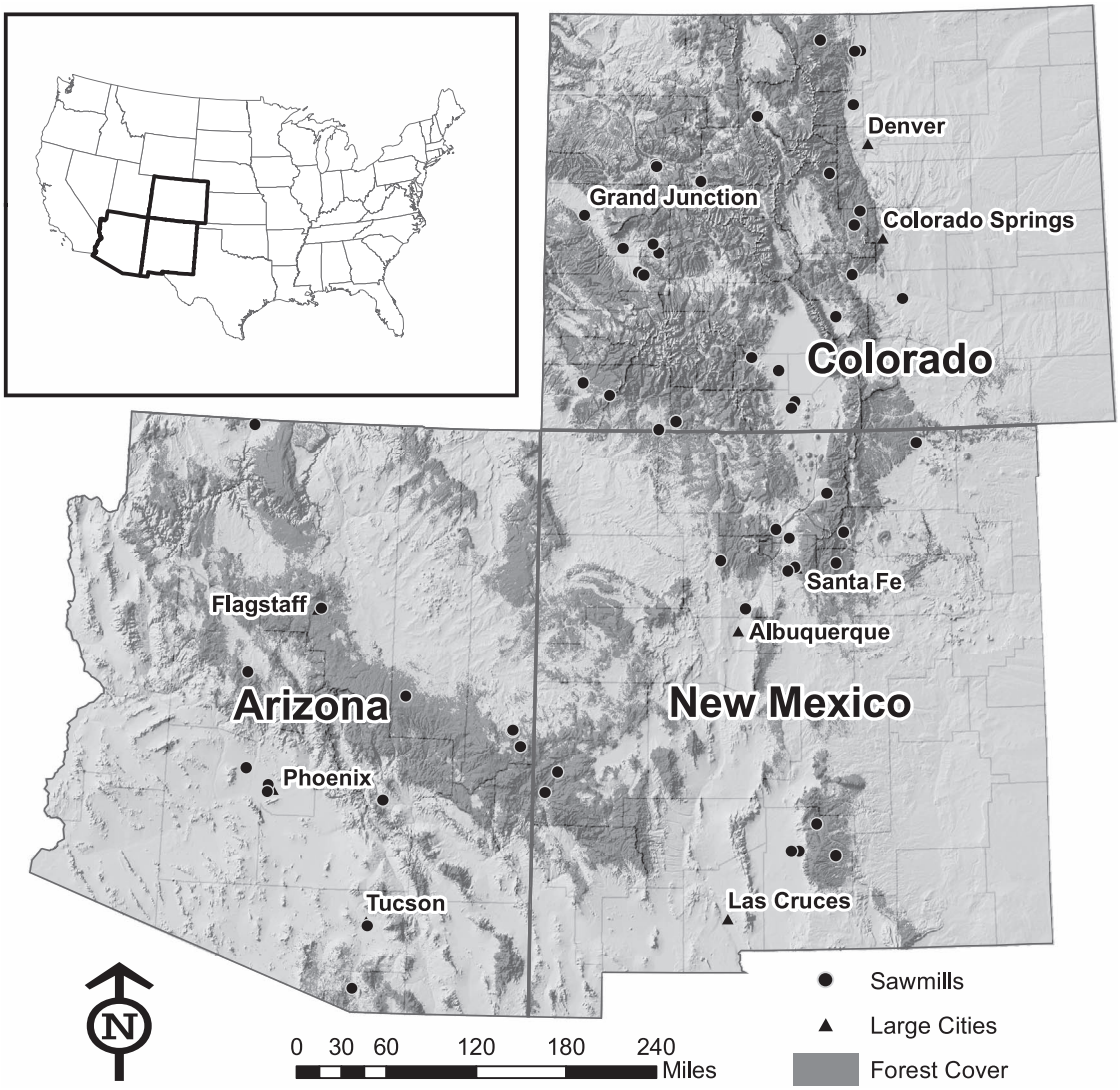

Figure 1.—Location of all sawmills in Arizona, Colorado, and New Mexico in 2012.

other regional- and national-level figures. This analysis includes 22 of the 61 sawmills active in 2012, which is a response rate of 36 percent, and these 22 sawmills accounted for 35 percent of 2012 lumber production in the three-state area.

As a frame of reference, a Bergman and Bowe (2008) study on the environmental impact of hardwood lumber production was based on 20 mills, which accounted for 6.5 percent of production in the region. This is within the 5 percent requirement for data quality recommended by the Consortium for Research on Renewable Industrial Materials (Consortium for Research on Renewable Industrial Materials 2001). Further, the fact that the average lumber production of respondent mills is roughly equal to the average lumber production of nonresponding mills decreases the likelihood of nonresponse bias in our sample. Characteristics of respondents compared with nonrespondents—mill size in this case—are among the strongest predictors of the relationship between response rate and nonresponse bias (Groves 2006, Groves and Peytcheva 2008).

In this article, we analyze only energy consumption on the premises of each sawmill and exclude energy used in other segments of the supply chain, including transportation of raw materials and finished goods. Likewise, emissions estimates are based upon on-site energy consumption and do not include emissions from energy consumed off-site, such as diesel fuel used in harvesting and transportation, for example. Emissions associated with the electricity generated off-site but consumed on-site at sawmills are included. Data from the survey are aggregated and summarized to protect confidentiality.

Fuel consumption and energy

The unit of energy reported in this analysis is the British thermal unit, which is the amount of energy needed to raise the temperature of 1 pound of water at maximum density through 1°F. We express energy consumption in orders of magnitude of British thermal units, where each ''M'' represents 10^3 Btu. Though not an accepted international system (SI) unit, the British thermal unit is a common energy measurement in the United States, and is used by the industry in the Southwest. For comparison with SI units, we

note that 1 Btu is equivalent to 1.055 kJ. Lumber production and associated compound units are presented in thousand board feet (MBF) lumber tally, which is the standard unit of production used in the region.

The sawmills in this study all had different mixes of fuels used on-site for lumber manufacturing, which we categorize as either nonrenewable (generated from fossil fuels or nuclear reaction) or renewable (generated from nonfossil and nonnuclear sources). In this analysis, on-site wood and bark combustion and those portions of electricity produced from hydroelectric dams, solar energy, and wind are considered renewable. No sawmills in this study had on-site solar, wind, or geothermal capacity.

Woody biomass

Although electricity production using steam turbines occurs at some forest products mills, wood and bark are primarily used to fire boilers to generate steam to supply heat to lumber-drying kilns, which are very energy intensive (Wengert and Meyer 1992, Bond 2008). In fact, lumber drying is typically the most intensive energy requirement at sawmills, followed by sawing and material handling (Wengert and Meyer 1992, Forest Products Laboratory [FPL] 1999). Biomass energy in the form of wood and bark consumed at sawmills in regions other than the Southwest is almost exclusively supplied from on-site mill residue. Because of the ambient atmospheric heat and aridity of the southwestern United States, and low equilibrium moisture contents (FPL 1999), very few sawmills in the region require drying kilns, and only one sawmill in this analysis reported operating a lumber-drying kiln. As a result, on-site sawmill demand for residue is very low, and as discussed below, residue markets are well established. There is, however, significant biomass in the form of logging residue associated with harvesting the timber processed by sawmills.

Logging residue is generated when timber products are harvested. Estimates of potentially available quantities of logging residue associated with the timber processed by the 22 sawmills in this analysis were developed using the same methods used in the TPO database (USDA 2015). Estimates of logging residue attributable only to the timber processed by sawmills in this analysis were derived using a combination of logging utilization studies (Morgan and Spoelma 2008, Simmons et al. 2014, Bureau of Business and Economic Research [BBER] 2015) and a whole tree volume study (Van Hooser and Chojnacky 1983). The logging utilization studies provided information for calculating bole residue associated with sawlog harvest, and the whole tree volume study provided information for calculating residue from limbs and tops. Substantial quantities of logging residue in excess of the quantities associated with sawmill timber use in this analysis exist in the region. For example, the TPO database shows that more than 7 million ft^3 (105,000 dry tons) of logging residues were generated from 2012 timber harvests in Arizona, Colorado, and New Mexico (USDA 2015).

The length of time that logging residue remains in the forest is highly variable and can affect the quality of the residue for use as fuel, most notably by changes in moisture content. Substantial drying will occur over time, and moisture content has a significant impact on the heating value of wood and bark (Jenkins et al. 1998). There is general consensus that a linear relationship exists between moisture content and higher and lower heating values of wood and bark (Shelton 1942, Bowyer et al. 2007). However, sawmills in this analysis did not use any measureable wood and bark for energy. To estimate potential energy substitution and emissions, we estimated moisture contents for each of the four most commonly harvested species—ponderosa pine, lodgepole pine, Engelmann spruce (*Picea engelmannii*), and Douglas-fir—which together constituted 90 percent of the total 2012 timber harvest in the three states (Sorenson et al. 2016). This was done using moisture contents for different portions of wood and bark reported in Wilson et al. (1987, 2010). The average of the four species' moisture contents was used to determine the higher heating values used in this analysis (Table 1). Using species-specific higher heating values (HHV) for combinations of wood and bark found in Wilson et al., energy contents were weighted on the basis of each species' proportion of the four species combined total: 53 percent ponderosa pine, 26 percent lodgepole pine, 11 percent Engelmann spruce, and 10 percent Douglas-fir. Last, weighted average energy contents were adjusted to reflect the average moisture contents on the basis of the following equation:

$$\text{Energy content} = \text{HHV} \times \left(1 - \frac{\text{percent moisture content (wet basis)}}{100}\right)$$

Results were used to inform the amount of logging residues that would be needed to offset alternative energy sources, as well as determine the associated emissions trade-offs. Because we cannot predict the moisture contents of wood and bark at the time of combustion, our estimates are based upon the highest likely moisture content in biomass. Therefore, less biomass would be required for equivalent energy substitution with further drying and lower biomass moisture content.

Fossil fuels and electricity

Energy content for fossil fuels consumed on-site at sawmills in these states in 2012 were obtained from the EIA (2015c) and are displayed in Table 2. The energy production portfolio of each sawmill's electricity provider was used to determine the portion of electrical energy attributable to renewable and nonrenewable sources. Electricity production in the Southwest United States is quite different from production in other regions, such as the Northeast and Southeast United States (Milota et al. 2005; Bergman and Bowe 2010, 2012). Many sawmills in this analysis purchased power from cooperatives supplied by a large

Table 1.—Assumed moisture contents and higher heating values for wood and bark.[a]

Species	Percent moisture content (wet basis)		Higher heating value (Btu/dry lb)	
	Wood	Bark	Wood	Bark
Douglas-fir	33.7	51.6	8,759	10,109
Engelmann spruce	44.1	47.6	8,653	9,018
Lodgepole pine	49.8	46.0	8,600	10,035
Ponderosa pine	52.4	33.1	9,120	9,516
Avg.	45.0	44.6	8,783	9,670

[a] Source: Wilson et al. (1987, 2010).

Table 2.—Assumed energy contents per unit of fuel.

Fuel	Unit	MMBtu/unit[a]
Diesel	Gallon	0.1374
Gasoline	Gallon	0.1205
Propane	Gallon	0.0913
Electricity	Kilowatt hour	0.0034

[a] MMBtu = million British thermal units.

generation and transmission association. Nine of the 14 electricity suppliers in this analysis obtained most or all of their power from the association, which in 2012 had an energy production portfolio that was 67 percent from coal-fired power plants, 16 percent from hydroelectric dams, 14 percent from contract sources, and the remaining 3 percent was obtained from a combination of wind, solar energy, and natural gas. The origin of contract power is unverifiable and considered nonrenewable in this analysis. Effectively, the association's energy portfolio was 18 percent renewable in 2012. Although a portion of contract electricity is likely to be renewable in this region, this cannot be verified. Therefore, the categorization of contract sources as nonrenewable in this study means the distribution of renewable and nonrenewable sources should be viewed as a minimum renewable scenario.

Emissions

In this analysis we report emissions of CO_2, CH_4, NO_x (nitrogen oxides), SO_x (sulfur oxides), and PM_{10} (particulate matter $\leq$ 10 μm). The emissions reported in this analysis are from fuels consumed on-site at the sawmills, and when possible from the fuels consumed off-site for generating electricity used by sawmills. As previously noted, the most energy-intensive component of lumber production throughout the country is drying sawn products in a kiln, and because only one sawmill in this analysis operated a drying kiln during 2012, overall energy consumption, and therefore emissions from energy use, are likely much lower at sawmills in the Southwest than for other regions of the country. For the fuels consumed on-site, emissions were estimated using a combination of fuel energy contents (Table 2) and emission factors obtained from the EPA. For electricity production, emission estimates were obtained from literature evaluating life-cycle inventories of both natural gas and coal-fired power plants. Emission factors and related references are displayed in Table 3. Although there are likely emissions associated with electricity production from solar energy, wind, and hydropower, typically from operations and maintenance of these facilities, to our knowledge there are no estimates of these emissions in the literature. Similarly, we were unable to locate estimates of operational emissions associated with nuclear power production. Last, because the sources of contract power are unidentifiable, we do not estimate emissions associated with contract power production, and further note that overall emissions reported here are underestimated because of these data constraints.

After almost any type of mechanical forest operation in the western United States, forest land managers continue to struggle with disposing of logging residue (i.e., biomass) by means other than burning on-site (Morgan et al. 2011). An abundance of time, energy, and financial resources have been devoted to researching and demonstrating value-added alternatives to open burning, most notably, removal for energy production at facilities close to the treatment site (Loeffler et al. 2010). However, if biomass is not used, it frequently must be disposed to meet federal or state laws for fire hazard reduction and other silvicultural requirements. Emissions associated with biomass burning in the woods are in different mixes and quantities than when burned in a controlled combustion environment such as a boiler (Loeffler and Anderson 2014). Table 3 displays emission factors for open-burning biomass.

Results and Discussion

Production and energy consumption

During 2012, total lumber production at sawmills in Arizona, Colorado, and New Mexico was 169 MMBF, or 49 percent of production capacity, accounting for less than 1 percent of total 2012 US lumber production, and slightly more than 1 percent of all western US lumber production (Zhou 2013). This analysis includes 22 of the 61 regional sawmills active in 2012, accounting for 36 percent of total regional lumber production, or 58.5 MMBF lumber tally. Annual production by sawmills in this analysis ranged from 0.1 to 9 MMBF, with average production of 2.7 MMBF. For comparison, nonrespondent sawmills averaged 2.8 MMBF in annual production. Total 2012 residue production at sawmills in the three states was 83,000 bone dry tons (BDT), of which 15,500 BDT was bark. Sixty-three percent of mill residue was used to make other products, 36 percent was used for energy (including firewood), and the remainder was unused. Table 4 displays the volumes and distribution of residue from the 22 sawmills in this analysis (Sorenson et al. 2016). In addition to sawmill residue production, 25,300 BDT of logging residue associated with the timber processed by the 22 sawmills was generated, which does

Table 3.—Factors used to estimate emissions from southwestern sawmill operations.

Fuel	CO_2	CH_4	NO_X	PM_{10}[a]	SO_X	References
Diesel fuel (lb/gal)	22.530	0.0	0.6045	0.0430	0.0398	EPA 1995, EIA 2015c
Gasoline fuel (lb/gal)	18.533	0.0	0.1964	0.0120	0.0101	EPA 1995, EIA 2015c
Propane (lb/gal)	12.5	0.0002	0.0130	0.0007	0.0011	EPA 1995, EIA 2015c
Electricity (lb/kWh)[b]	1.7612	0.0037	0.469	0.1688	0.4107	Spath et al. 1999, Spath and Mann 2000
Biomass—burn on-site (lb/ton)[c]	2,175.22	7.58	3.89	8.25	2.35	Yokelson et al. 1996, Hardy et al. 2001, Urbanski 2010[d]

[a] PM_{10} = particulate matter $\leq$ 10 μm.
[b] Weighted average of reported emissions from coal and natural gas-fired power plants based upon the proportion of electricity generated by coal and natural gas reported by sawmills in this analysis.
[c] Assume 30 percent moisture content at time of combustion and all but 5 percent of logging slash piles fully consumed.
[d] Sean Urbanski, Missoula Fire Science Laboratory, personal communication, 2010.

Table 4.—Distribution of sawmill residues in this analysis in 2012.

	Coarse	Fine	Bark	Total
Residues sold for products (BDT)[a]	21,590	17,128	13,585	52,303
Residues used for energy (BDT)	27,484	1,324	970	29,777
Residues not used (BDT)	0	16	916	932

[a] One bone dry ton (BDT) equals 1 ton of residue at 0 percent moisture content.

not include the smaller, nonmerchantable trees that may have been cut or killed during treatment.

Weighted average energy contents of wood and bark for the four most commonly harvested species in 2012, adjusted to moisture contents of 45 percent for wood and 44 percent for bark (wet basis), were determined to be 9.7 MMBtu/ton of wood and 10.9 MMBtu/ton of bark. Using the average wood and bark energy content, 260,770 MMBtu is contained in the calculated logging slash total. As with biomass used for energy substitution, it is important to note that the energy content of logging residues will vary on the basis of moisture content, and that our results likely represent the highest possible usage with the combustion technology appropriate for these moisture contents.

Fuel and associated energy consumption at sawmills in the three states in 2012 are displayed in Figure 2 and Table 5. The 22 southwestern sawmills in this study consumed approximately 64,800 MMBtu of energy in 2012. Diesel fuel constituted the vast majority of energy consumption at sawmills, representing 64 percent of total energy. Electricity made up 35 percent of total energy, gasoline made up 3 percent, and propane and wood combined made up 1 percent. All sawmills used a substantial amount of diesel fuel on-site. Four sawmills reported being off the electric grid entirely, 12 reported using gasoline, and 6 reported using propane on-site. None of the respondent sawmills reported using biomass for energy other than for woodstove heat. As noted earlier, on-site sawmill demand for residues is very low, primarily because of the prevalence of air-drying lumber. All gasoline, 94 percent of diesel, and 71 percent of propane was reported as used for on-site support equipment such as rolling stock (e.g., log loaders, forklifts). Three sawmills reported using diesel to power generators for electricity production, and a small amount of diesel was reported to fuel a drying kiln at the single sawmill that reported operating a drying kiln in 2012.

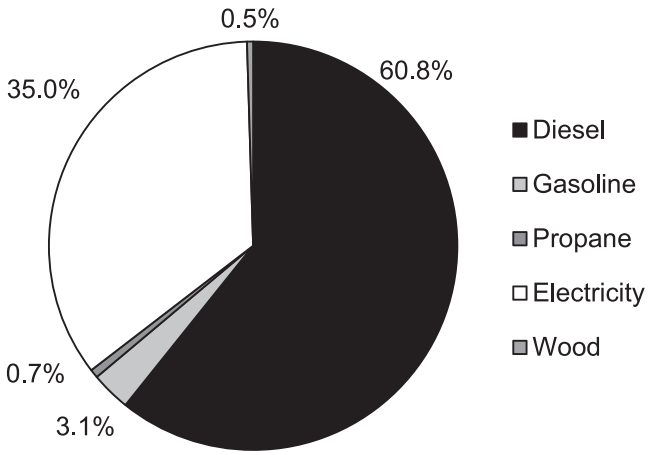

Figure 2.—Categorical distribution of energy consumed on-site at sawmills in this analysis in Arizona, Colorado, and New Mexico in 2012.

Southwestern sawmills consumed a substantial amount of grid electricity in 2012, which provided 35 percent of total energy. Overall, the aggregate energy portfolio of southwestern sawmills is tilted toward nonrenewable energy sources; all sawmills that used grid electricity were supplied by the association or cooperatives that either produced or obtained a major portion of power from coal or natural gas power plants. Four sawmills obtained a portion of power from nuclear sources; 15 obtained a portion of power from contract sources; and all but one sawmill obtained some power from hydroelectric, solar, or wind sources. Four sawmills reported using no grid electricity. Of the total grid electricity consumption, 84 percent was generated from nonrenewable sources (coal, natural gas, nuclear, or contract sources) and 16 percent from renewable sources (hydroelectric, wind, or solar). Fifty-seven percent of grid electricity consumed at sawmills in this analysis was obtained from coal, 15 percent from contract sources, 12 percent hydropower, 9 percent natural gas, 4 percent nuclear, and 3 percent wind or solar.

Table 6 displays the distribution of fuels used to generate electricity off-site by the association and cooperatives. Figure 3 displays the distribution of fuels that the association and cooperatives used to generate grid electricity for each sawmill in the sample. Aside from solar, wind, natural gas, and contract sources, the percent distribution of fuel sources to generate electricity off-site is similar to the

Table 5.—Total fuel and energy consumption on-site at sawmills in this analysis in 2012, and fuel energy consumption on a production basis.[a]

Fuel	Total fuel consumed	Total MMBtu consumed on-site	MMBtu percent of total	MMBtu/MMBF of lumber
Diesel (gal)	286,593	39,375	60.7	673.1
Gasoline (gal)	16,827	2,027	3.1	34.7
Propane (gal)	4,860	444	0.7	7.6
Electricity, nonrenewable (kWh)	5,654,972	19,295	29.8	329.9
Electricity, renewable (kWh)	983,481	3,356	5.2	57.4
Wood, 45% moisture (ton)	60	311	0.5	5.3
Total from nonrenewable		61,154	94.3	1,045.5
Total from renewable		3,666	5.7	62.7
Grand total		64,821	100	1,108.2

[a] MMBtu = million British thermal units; MMBF = million board feet.

Table 6.—Distribution (percent) of fuels used to generate electricity off-site in 2012 for sawmills in this analysis.

Fuel	Mean	Minimum	Maximum
Coal	57.0	10.7	66.7
Natural gas	8.5	1.1	40.5
Nuclear	3.9	0	27.1
Contract	15.0	0	47.6
Hydroelectric	12.1	0	20.7
Solar and wind	3.4	0.4	20.4

percent distribution of fuels used to produce electricity consumed on-site. Approximately 1 percent of total energy consumption was produced on-site at sawmills with diesel generators. Although we have categorized contract sources as nonrenewable, it is likely that an unknown portion of contract sources are from renewable sources, and total renewable energy consumption is underestimated. For example, a 27-MW biomass-fueled electric generating facility was in operation in 2012 in Snowflake, Arizona, yet neither the association nor cooperatives specifically listed biomass as an energy source in their portfolios.

Recall that sawmills in this analysis were provided with electricity generated from mostly nonrenewable sources, and a substantial portion of total on-site energy consumption at these sawmills was from electricity. Although there are few options regarding a firm's ability to choose an electricity supplier, the Renewable Portfolio Standards in New Mexico and Colorado require all electric utilities and cooperatives to obtain at least 10 percent of electricity from renewable sources by 2020. The Renewable Portfolio Standard for Arizona requires all utilities and suppliers to obtain 15 percent of electricity from renewable sources by 2025. During 2012, 18 and 16 percent of the electricity provided to sawmills in New Mexico and Colorado, respectively, were generated from renewable sources, whereas 13 percent of the electricity provided to the Arizona sawmills in this analysis was generated from renewable sources. Last, four sawmills consumed 61 percent of the total grid electricity purchased by the 18 sawmills that used electricity.

Figure 4 displays the distribution of all fuels consumed on-site. Only 6 percent of the total sawmill energy consumed on-site was derived from renewable sources. Of the 3,670 MMBtu of renewable energy consumed, 92 percent was obtained from electricity generated from renewable sources, and the small quantity of wood used accounted for 8 percent of renewable energy consumption. Conversely, 94 percent (61,150 MMBtu) of total sawmill energy consumed on-site was derived from nonrenewable sources. Of the total energy generated from nonrenewable sources, diesel fuel accounted for 64 percent, electricity from nonrenewable sources accounted for 32 percent, gasoline accounted for 3 percent, and propane accounted for 1 percent. To put the sawmills' nonrenewable energy consumption into perspective, 61,150 MMBtu is equivalent to the energy contained in 10,540 barrels of crude oil, 26 railcars of coal, or 509,600 gallons of gasoline, which is enough gasoline for 10.9 million passenger vehicle miles.

Nationwide, the sawmill industry consumed 232 million MMBtu in 2010 (EIA 2010) and produced 24,800 MMBF of lumber (Howard and Westby 2013)—approximately 9,355 Btu per board foot produced in 2010. Though similar national-level data for 2012 are not available to make a perfect comparison, sawmills in this analysis compared extremely favorably with the national average. The 22 sawmills in this analysis had a total energy consumption of 61,150 MMBtu and produced 58.5 MMBF of lumber in 2012, for an average of 1,045 Btu per board foot of lumber. This is approximately 11 percent of the 2010 national average; however, we acknowledge that methodologies to estimate both energy consumption and lumber production are quite different for this regional analysis compared with the national analysis. Using similar methods to compare the southwestern sawmills with Montana sawmills, which consumed 3,830 Btu per board foot in 2009 (Loeffler et al. 2016), southwestern sawmills used about 27 percent of

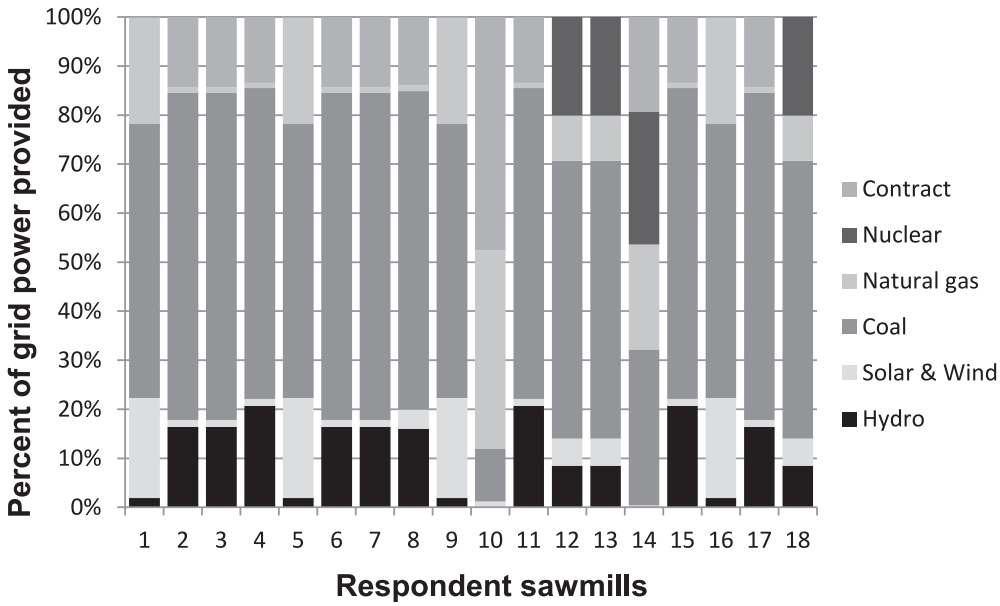

Figure 3.—Distribution of fuel sources for generating the grid electricity consumed on-site at sawmills in this analysis in Arizona, Colorado, and New Mexico in 2012.

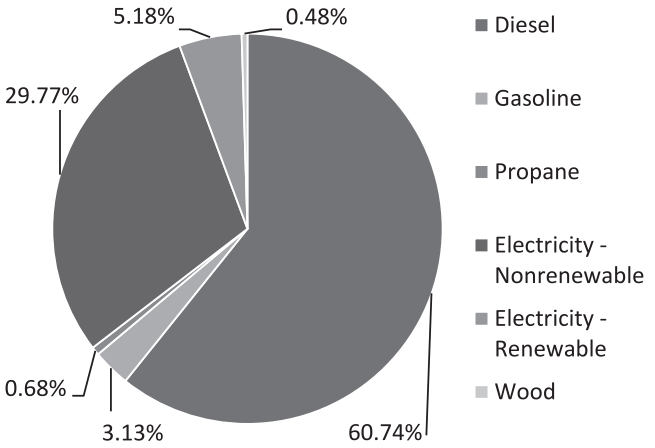

Figure 4.—Distribution of all energy consumed on-site at sawmills in this analysis in Arizona, Colorado, and New Mexico in 2012.

the energy per board foot consumed by Montana sawmills. This is likely owing to many factors, including sawmill equipment and configuration, number of operating shifts, species mix, fuels consumed, climate, and energy efficiency. Most notably, however, the prevalence of air-drying lumber in the Southwest eliminates the use of highly energy-intensive drying kilns, which is common in Montana and most other regions.

The sawmill industry in the United States is a major producer and user of renewable energy. In contrast, renewable energy production and consumption on-site at these sawmills is very low. Their reported renewable energy consumption is very closely tied to the proportion of electric grid power attributable to renewables. Given the favorable climate conditions for air-drying, associated lack of dry kilns, relatively small production capacity of most facilities, and low electricity use per thousand board feet, there does not seem to be much need or opportunity for biomass energy production on-site. However, the use of biomass boilers could have an important connection to residue management. Sawmills and timber purchasers look for the most profitable, or least costly, ways to dispose of their residue. Local markets for sawmill residue are currently more limited in the Southwest than in other regions because there are no pulp mills or reconstituted board plants. However, these sawmills are small, low-volume producers and geographically dispersed, which may allow them to sell effectively into local bioenergy markets where possible and capitalize on further market development, rather than use bark and other residue for on-site heat and power like many large sawmills in other regions. This is an interesting topic for further study in the context of distributed scale biomass energy systems, including biomass heating and combined heat and power systems for institutions, as well as small- to medium-scale biomass power plants. This result also supports the importance of high-resolution state and regional analyses to complement sector-level and national studies, which do not always account for important regional variability in the industry.

Emissions

Emissions of CO_2, CH_4, NO_X, SO_X, and PM_{10} generated by sawmills in the southwestern United States have not been documented generally or reported in the literature. Using emission factors referenced in Table 3, total emissions from sawmilling operations in the three states were estimated; Table 7 displays the total emissions produced by sawmills in this analysis by fuel source. Off-site electricity generation for consumption at sawmills constituted the majority of all emissions in this analysis: 62 percent of CO_2, 94 percent of NO_X, and 99 percent of CH_4, SO_X, and PM_{10}. Diesel fuel, which supplies the majority of on-site energy, comprises 36 percent CO_2, 0 percent CH_4, 5 percent NO_X, 0.4 percent SO_X, and 1.1 percent of PM_{10}. Other CO_2 emission sources are from gasoline (1.6%), wood (0.6%), and propane (0.3%). Diesel fuel combustion contributed 1.1 percent of PM_{10} emissions, 5.3 percent of NO_X emissions, and 0.4 percent of SO_X emissions. Gasoline fuel combustion contributed 1.6 percent CO_2, and only 0.1 percent of NO_X emissions, with no other notable emissions. Emissions from electricity generated on-site by diesel and gasoline fuels were included in these estimates.

It is likely that the majority of logging residues associated with the timber processed by the 22 sawmills in this analysis required disposal of some kind for compliance with federal or state laws, and for other silvicultural purposes. Sawmills included in this analysis processed slightly more than 49 MMBF (Scribner) of timber, which when delimbed and processed in the forest, yielded 25,300 BDT of logging residues. Emissions associated with burning logging residues in the forest were estimated using emission factors presented in Table 3, and assuming 30 percent moisture content at the time of combustion and all but 5 percent of the logging slash burned being fully combusted. Table 8 displays the estimates: 27,536 tons of CO_2, 96 tons of CH_4, 49 tons of NO_X, 104 tons of PM_{10}, and 30 tons of SO_X were emitted from burning the 25,300 tons of logging slash. Emissions of CO_2 and CH_4 from pile-burning logging residues are significantly greater than the total emissions from sawmilling the timber associated with the logging residues, at 65 and 87 percent, respectively. However, PM_{10}, NO_X, and SO_X emissions from pile burning are substantially less than those from sawmilling operations.

Considering that the Renewable Portfolio Standards for the three states require that a larger share of electricity production comes from renewable sources, and that the majority of electricity production comes from coal-fired power plants, cofiring logging residues with coal may be a viable option to meet the Renewables Portfolio Standards. Loeffler and Anderson (2014) have modeled the emissions reductions associated with cofiring residues with coal in Colorado. The energy contained in the electricity consumed at sawmills in this analysis is equivalent to 2,200 tons of logging residues, and if the 2,200 tons were cofired with coal, this would displace 1,100 tons of coal. If all 25,300 tons of logging slash were cofired immediately after operations, 12,300 tons of coal would be displaced, which is equivalent to approximately 100 railcars of coal. Yet, often because of financial constraints, large quantities of unutilized logging slash is burned on-site at logging units because the cost of logistics to process and deliver the material exceeds the delivered price of biomass fuel. Although the literature discussing this topic is vast (Loeffler et al. 2010), additional research is necessary to determine financially optimal methods for utilizing otherwise wasted wood resources, especially logging slash.

Table 7.—Total selected emissions (lb) from southwestern sawmill operations in this analysis in 2012.[a]

Fuel	CO_2	CH_4	NO_X	PM_{10}	SO_X
Diesel fuel	6,816,311	0	182,909	13,033	12,042
Gasoline fuel	312,318	0	3,310	202	170
Propane	60,750	1	63	4	5
Electricity	11,691,643	24,562	3,113,434	1,120,571	2,726,413
Wood	119,546	13	300	178	15
Total	19,000,569	24,576	3,300,017	1,133,957	2,738,645
lb/MBF	324.8	0.4	56.4	19.4	46.8

[a] PM_{10} = particulate matter $\leq$ 10 μm; MBF = thousand board feet.

It is difficult to provide more detailed analysis while maintaining confidentiality, but even though overall southwestern sawmill energy use is low, the energy mix of the southwestern sawmilling industry highlights a broader issue related to expansion of biomass energy and other renewable energy sources. The markets for sawmill residues are well established, and although markets fluctuate, in 2012 just 1.1 percent of residues from sawmills in this analysis went unused (Table 4). In 2012, 36 percent of residues from sawmills in this analysis were converted to energy, mostly in the form of firewood, with the remainder serving as raw material for other products. The distribution of sawmill residues displayed in Table 4 asserts that clean residues have higher value than fuel. On the basis of the fact that sawmill residues are already leveraged, additional bioenergy capacity at sawmills is likely to be fueled by logging slash, and not sawmill residues. Given that the majority of on-site sawmill energy consumption comes from diesel fuel, specific sawmills are potential candidates for additional on-site energy production in the form of combined heat and electricity production. Although not addressed in this research, financial analyses of the benefits and costs of additional heat and power production capacity is clearly warranted.

Although opportunities for new bioenergy capacity at sawmills in this region appear limited, primarily because of low heat demand and small sawmill size, these results show potential emissions and renewable energy benefits from using logging slash produced by this industry rather than burning it in the forest for disposal. Dedicated biomass power plants like the 27-MW facility in Snowflake, Arizona, and the 11-MW plant in Gypsum, Colorado, are suitable options. Wood pellet production is also an option, although industrial pellets are likely a stronger possibility than residential pellets because of the higher ash content in logging residue when compared with roundwood. Such facilities may benefit from national and state incentives for renewable energy. For example, there are facilities in all three states that are presently qualified biomass conversion facilities under the Biomass Crop Assistance Program, which provides matching payments on approved biomass contracts. Such facilities can also contribute to meeting state Renewable Portfolio Standards, and improve the financial viability of forest restoration and fuel treatments by providing markets for treatment residues.

Furthermore, expanding the bioenergy industry in the Southwest will only occur when feedstock markets are secure. The southwestern states in this analysis are heavily forested with many millions of acres in need of restoration, have very low lumber production energy requirements, and need to expand renewable energy production. Consequently, this region is well positioned to restore forested landscapes, expand rural employment and bioenergy production, and significantly contribute to climate change mitigation.

Table 8.—Total selected emissions from pile-burning logging residues associated with timber processed by southwestern sawmills in 2012.[a]

Emission	Total logging residue burning emissions (lb)
CO_2	55,072,000
CH_4	192,000
NO_X	98,000
PM_{10}[b]	208,000
SO_X	60,000

[a] Assume 30 percent moisture content and all but 5 percent of the logging slash fully combusted.

[b] PM_{10} = particulate matter $\leq$ 10 μm.

Conclusions

Unlike the forest industry in much of the United States, we have found that the majority of energy used on-site at sawmills in Arizona, Colorado, and New Mexico is derived from nonrenewable sources. This is primarily owing to both on-site use of large quantities of diesel fuel and the large percentages of grid-delivered electricity generated from fossil fuels. Most of the industrial, commercial, and residential energy demand in this region is met by nonrenewable sources, and individual wood products facilities have similar portfolios. In addition, southwestern sawmills generally do not use drying kilns, which consume large amounts of energy and are usually served by wood-fired boilers. In the short term, biomass is unlikely to be able to displace the liquid fuels used at these sawmills, but increasing social demand for renewable energy could lead to improved markets for biomass energy from which regional sawmills may be able to benefit. Increased biomass energy is also likely to have emissions benefits, especially if logging residues are used as fuel. More broadly, regional-level information like this can help guide state and local energy policy, as well as inform more detailed life-cycle inventories and other analyses that quantify environmental costs and benefits beyond the gates of wood products facilities.

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