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Emissions of wood pelletization and bioenergy use in the United States

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ABSTRACT

Despite a significant increase in United States biomass energy sector activity, including domestic bioenergy deployment and wood pellet production for overseas exports, the associated criteria pollutant emissions are not well quantified in current regulatory emissions inventories. We present an updated U.S. emissions inventory, with emphasis on wood-based biomass pretreatment (e.g., drying, condensing, storage of wood pellet) and the use of biomass for energy generation. As a significant number of wood pellet production facilities are not included in current inventories, we find that this sector's emissions could be potentially underestimated by a factor of two. Emissions from biomass-based facilities are on average up to 2.8 times higher than their non-biomass counterparts per unit energy. We estimate that 2.3 million people live within 2 km of a biomass facility and who could be subject to adverse health impacts from their emissions. Overall, we find that the bioenergy sector contributes to about 3–17% of total emissions from all energy, i.e., electric and non-electric generating facilities in the U.S. We also review some drivers of bioenergy expansion, such as various feedstocks and technologies deployed with an emphasis on wood-based bioenergy and discuss their implications for future air quality and health impacts.

1. Introduction

Wood burning has provided humanity with heat and light throughout history. In recent decades, modern bioenergy has been described as a reliable, dispatchable contributor to base load power generation and as a "bridge fuel" in the transition to sustainable energy sources. Despite this lengthy history and bioenergy's present-day ubiquity, biomass burning emits both substances of health concern (such as fine particulate matter) and those that influence global warming (including both greenhouse gases and radiative forcers such as black carbon (BC) [1,2]. Yet their potential for adverse impacts remains largely underappreciated. As the transition to sustainable and renewable energy sources gains momentum, understanding potential health impacts and gaps in knowledge related to decarbonization remains critical [3].

Modern bioenergy and bioenergy with carbon capture and storage feature in the majority of climate change mitigation scenarios and illustrative pathways presented by the Intergovernmental Panel on Climate Change (IPCC) that achieve mitigation targets of 1.5–2 °C [4], though constraints on land use and water availability may attenuate their technical potential [5–7]. Interest in decarbonization has led to the adoption of supportive policies for bioenergy in the U.S., the European Union, and elsewhere [8], but non-biofuel bioenergy use in the U.S. has stayed stable over the last two decades and remains modest. As of 2022, in the U.S., fossil fuels remain the primary source of energy for electricity generation, with natural gas, coal, and petroleum accounting for around 59% of total electricity generation; nuclear energy accounting for about 18% of electricity generation; and renewable energy contributing the remaining portion (10.2% wind energy, 6.2% hydropower, 3.5% solar energy, 1.3% biomass, and 0.4% geothermal) [9] (see S1 for further discussion of the U.S. grid mix).

Biomass feedstocks for energy include wood and wood residues, post-consumer wood and paper products, mill wastes (including sawdust and black liquor, a by-product of the pulping process), forestry residues, agricultural residues, food wastes, and other biomass-based elements of municipal solid waste streams, as well as animal manure and sewage (used to produce biogas) [10]. The U.S. burns around 12% of its municipal solid waste (MSW) with energy recovery, with biomass comprising about 60% of MSW by weight and accounting for around 45% of electricity generated from MSW [10]. Direct combustion (burning) of biomass (often in stoker boilers or fluidized bed boilers) remains most prevalent, though thermochemical conversion techniques

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such as pyrolysis and gasification are becoming more common [10,11], as is interest in unconventional biomass feedstocks. Around 2% of U.S. homes are heated primarily with wood [12].

Pretreatment of biomass to improve fuel quality or achieve certain specifications for use in systems at all scales is common, and may include techniques such as washing, leaching, drying, densification, pelletization, and torrefaction [13]. One increasingly prominent pretreatment method is pelletization, which has lower moisture content and burns more efficiently than raw materials such as wood chips or logs (see S2 for more information on wood pellet production). Global wood pellet production has steadily increased from ~2 million metric tons in 2000 to ~32 million metric tons in 2017, mainly in the European Union (EU) and North America, with production capacity of wood pellets in the Southeastern U.S. increasing from less than 0.5 million tons per year (tpy) before 2009 to around 7.3 million tpy by 2017 [14,15]. Feedstocks are primarily exported to Europe, though markets in Asia are also growing [16]. Due to outdated greenhouse gas accounting guidelines, bioenergy deployment can reduce reported emissions for countries who import feedstocks to displace coal [17], and demand is expected to increase.

As with fossil fuels, the burning of biomass emits carbon dioxide (CO_2). Some maintain that because biomass contains carbon previously sequestered from the atmosphere, it has a "neutral" and therefore negligible effect on atmospheric CO_2 levels, though this is contested (e.g., Refs. [18,19]). The latest IPCC report states with "high confidence" that bioenergy deployment "can lead to either increased or reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and how, and where, the biomass is produced" [20]. For example, in life cycle assessment, depending on the assumptions, methodological decisions, and spatial and temporal scope defined by researchers (such as whether to include emissions related to forest regrowth or fossil fuel and biogenic emissions in the supply chain related to harvest, transport, drying, pelletization, and storage), the net emissions impact of woody or forest-derived bioenergy may be assessed to be neutral, positive, or negative [6,18,19,21–29]. Bioenergy deployment could displace other energy sources in the U.S. energy mix, with potential benefits related to fossil fuel displacement but potential adverse effects related to displacement of zero-emitting energy sources such as wind and solar [30]. Irrespective of net emissions across the life cycle, at the stack, assuming 100% oxidation of fuel carbon content, wood and wood residues release approximately as much CO_2 per unit of energy generated (93.80 kg CO_2/MMBTU) as coal (93.28–103.69 kg CO_2/MMBTU), and significantly more than is released by natural gas (53.06 kg CO_2/MMBTU), though other biomass-derived fuels such as landfill gas/biogas may release less CO_2 per unit of energy (52.07 kg CO_2/MMBTU) [31].

Beyond CO_2 and other greenhouse gases (namely, methane (CH_4) and nitrous oxide (N_2O)), biomass burning results in the release of both gaseous pollutants (including secondary aerosol precursors such as sulfur dioxide (SO_2) and ammonia (NH_3), and ozone precursors such as nitrogen oxides (NO_X)), volatile organic compounds (VOCs), and both filterable and condensable particulate matter, primarily smaller than 2.5 μm ($PM_{2.5}$) (see Table S1; [32,33]). Burning of biomass (both natural and anthropogenic) releases dioxins, furans, and dioxin-like polychlorinated biphenyls, a family of persistent organic pollutants [34,35]. Biomass combustion typically emits significantly lower levels of SO_2 compared to coal combustion due to the lower sulfur content of biomass [36]. Biomass combustion also releases significantly lower levels of "fuel-bound NO_X" in comparison to coal, though additional NO_X may be emitted during combustion derived from reactions with atmospheric nitrogen [11,33]. Residential wood heating is the largest source of $PM_{2.5}$ in the U.S. after dust from roads and agriculture and wildfire/prescribed fires and is also responsible for emissions of polycyclic aromatic hydrocarbons (PAHs), NO_X, black carbon, acrolein, and formaldehyde [37]. Similarly, combustion of MSW generates PM, NO_X, VOCs, PAHs, dioxins, and other harmful pollutants (see Table S1; [34,38]). Pretreatment of biomass for energy generation to increase density and homogeneity may also lead to pollutant emissions. Drying, pelletization, and storage of wood for bioenergy applications result in emissions of condensable PM and VOCs classified as hazardous air pollutants (HAPs) by the EPA, such as acrolein [39,40].

The risks to human health associated with exposure to unabated biomass smoke are well documented in the context of low- and middle-income countries and are increasingly being documented in high-income countries, where adverse health effects from both long- and short-term exposure have been observed [41,42]. Relatively few studies have explored the public health effects of MSW combustion in waste-to-energy plants [43,44]. However, commercial and industrial biomass-fired boilers typically employ various control devices that can reduce emissions of PM by 80% or more, including mechanical collectors, wet scrubbers, and electrostatic [45]. Municipal solid waste incinerators also employ this pollutant control technology [46]. Modern wood stove design, driven by more stringent federal regulations on wood stove emissions and advances in technology, can reduce emissions compared to open fires and older stoves, though there is no stack testing or enforcement of emissions limits for these devices [37].

Fossil fuel pollution poses significant risks to public health globally, increasing morbidity and estimated to be responsible for 8.7 million premature deaths annually [47]. In the U.S., premature deaths attributable to emissions from the electricity sector have gone down from 21,000 in the year 2005 [48] to be between 4000 and 9000 [49,50] in the year 2018 due to reductions in emissions from the sector. An energy transition toward zero-emitting energy sources could further reduce both premature mortality- and morbidity-related health effects. If, however, the U.S. increases the share of bioenergy as it reduces the share of fossil fuel energy in its mix, emissions from bioenergy could present greater concerns to public health. Buonocore et al. [51] utilized three reduced complexity models and emissions inventory data to reconstruct the changes in health impacts due to $PM_{2.5}$ exposure from stationary fuel combustion sources in the U.S. from 2008 to 2017 from replacing coal with natural gas and biomass and reported biomass and wood are the leading sources of stationary source air pollution health impacts in 24 states. In many states, emissions from biomass and wood combustion have overtaken coal as the leading source of mortality impacts [51].

Other studies have assessed the potential impacts of increased biomass use. Carreras-Sospedra et al. [52] employed a photochemical model to evaluate air quality impacts of various bioenergy deployment scenarios in California, U.S., and found that maximizing biomass combustion for electricity in the state could increase NO_x emissions and PM and ozone concentrations in large areas of the state, including the heavily burdened Central Valley. Scenarios that deployed biomass gasification and compressed natural gas from biomass for vehicle use could offer superior outcomes for GHG emissions as well as for air quality [52].

Mailloux et al. [53] applied the EPA's CO-Benefits Risk Assessment (COBRA) screening tool [54] to access health benefits resulting from the removal of $PM_{2.5}$-related emissions from six energy-related sectors including electric generation, residential/commercial, industrial, onroad vehicles, nonroad vehicles, and oil and gas production/refining in the contiguous U.S. (CONUS). Each year more than 50,000 premature deaths could be avoided and over $600 billion in health benefits could be saved from the avoided illness and deaths from eliminating emissions from these energy-related sectors [53]. Of the total primary $PM_{2.5}$ emissions from these energy-related sectors, about 34% and 12% are from residential wood burning and the combustion of wood/bark waste by the industry, respectively; 51% are from fossil fuel combustion which is the dominant source of SO_2 (94%) and NO_X (95%) emissions from these sectors [53].

Recent analysis exploring the modeled effects of various policy scenarios on the U.S. power sector found that expansions in the national energy mix of co-firing of woody biomass with coal undermined decarbonization goals and reduced welfare, as co-firing delayed the

retirement of coal facilities, displaced generation by cleaner alternative energies, and even increased modeled NO_X emissions because of losses in generation efficiency [55]. Similarly, Schmid et al. [56] modeled the effects of decarbonization strategies in the EU.

Finally, analysis from the EU suggests that increased consumption of bioenergy (from residential heating to utility-scale electricity generation) has increased mortality rates in developed and developing EU-28 countries during the period 1990 to 2018 [57]. More detailed overview of the health and climate impacts of biomass use for heat and electricity in both indoor and outdoor settings in Europe are discussed in Ref. [58].

The risks to health of bioenergy emissions, as discussed above, require policymakers to be able to carefully evaluate the long-term implications of decarbonization policies, including those that promote or subsidize bioenergy, on public health, air quality goals, and more. In the U.S., however, data on the current and potential contributions of pollutants from bioenergy remain scarce.

The objectives of this study are thus to fill in existing knowledge gaps on emissions from bioenergy and wood pellet manufacturing with a refined quantitative emissions inventory, and to further improve understanding of potential impacts of the sector in the U.S. Throughout this study we review several drivers of bioenergy expansion and the various feedstocks and technologies deployed, with an emphasis on wood-based bioenergy. We then outline pollutants of concern emitted during feedstock pretreatment and bioenergy generation. We present a newly assembled inventory of air pollutant emissions related to both woody biomass pretreatment and bioenergy (all feedstocks) production in the U.S., with an emphasis on wood-based biomass pretreatment and energy generation, which can facilitate comparison with other emission sources. We also assess the proximity of these facilities to urban areas. We conclude with discussion of potential implications of increased reliance on bioenergy generation and biomass feedstock pretreatment in the U.S. Our objectives, however, are limited to quantifying and evaluating emissions estimates from processing and consumption of biomass, and future studies are required to improve estimates of emissions across the full life cycle of bioenergy. Furthermore, this analysis could support future assessment and quantification of the air quality and health impacts of these growing sectors in the U.S.

2. Materials and methods

We found no existing unified inventory of wood pellet manufacturing (WPM) and bioenergy generation (BIOE) facilities. We thus analyzed various reference datasets to synthesize a list of WPM and BIOE facilities in the U.S., which we believe to be the most comprehensive one at the time of this study. Similarly, we found no existing inventory of criteria pollutant emissions from these facilities. Methodological details on emissions estimation for WPM and BIOE facilities are discussed below.

Although the U.S. EPA's National Emissions Inventories for base year 2017 (NEI 2017; [59]) captures emissions from smokestacks related to biomass used for heat or electricity generation, additional information was needed to estimate emissions from fuel pretreatment processes (i.e., wood pellet manufacturing). To understand the net emissions associated with bioenergy use, we used the NEI database, and supplemented it with industry data and WPM permits. We identified WPM facilities using the commercial database managed by Biomass Magazine (BM) [60]. As of March 2022, the BM dataset lists 122 pellet plants, among which 117 facilities are operational, four facilities are under construction, and one is proposed. The BM dataset reports only production capacity for WPM. We also relied on the U.S. Energy Information Administrator (EIA) Monthly Densified Biomass Fuel Report, which tracks production data and operation status of BM facilities from 2017 onward [61]. As of December 2021, EIA reports 132 WPM facilities, 97 of which are currently operating or temporarily not in operation.

Neither the BM nor EIA dataset reports emissions from WPM. To compile emissions information, we mapped the WPM to NEI 2017 [59] using the WPM's geo-locations and their names. We also searched for the facilities' names and their North American Industry Classification System (NAICS) codes in the NEI 2017 database. NAICS codes 321999, 32199 and 3219 are commonly assigned to WPM in the NEI 2017. However, these NAICS codes are not dedicated to WPM (in fact, there are 546 facilities in the NEI 2017 which share the same NAICS codes). As a result, only 38 WPMs were identified in the NEI 2017, which points to a potential underestimation of emissions from WPM. We gathered emissions data for the remaining WPM facilities by searching state regulatory agency databases for their issued air quality permits (Title V and non-Title V permits, hereafter "air permit") which contain detailed descriptions of the facilities, their allowable emission limits, and, in some cases, their actual emissions. We identified 153 WPM facilities across 36 states from which 97 air permits were located. The permits that we located were issued between May 2011 and February 2022. Overall, 79 (81%) of the 97 permits were issued in or after 2018. Combining the air permits with BM and EIA datasets, we identified 126 operational WPM facilities as of April 2022, though we note that the number of facilities is dynamic. Summaries of identified WPM facilities from each dataset are presented in Table S2. We reviewed the history of WPMs' violations of air quality permits to identify gaps between their actual emissions and their issued permit.

Many small-scale facilities (production levels <5000 oven dried ton a year (ODT/yr)) are exempt from permit requirements. Furthermore, only 71 out of the 97 located air permits contain useable emissions information (i.e., numerical emission limits were reported). For the 55 out of 126 WPM facilities without available permits, emissions are extrapolated from emissions at facilities that share the same production processes and capacity. For example, for a small-scale WPM that is not equipped with a wood dryer or boiler, its emissions are estimated based on emissions from similar WPMs without a dryer since these facilities are not associated with emissions of NO_X, CO and SO_2 (see S2 for more details).

In air permits, the potential emissions from each WPM facility were calculated based on emissions factors that were mainly derived from EPA's AP-42 [62] stack test results of the facility in prior years or stack test results from a similar operating facility. Among pollutant emissions, SO_2 is often omitted in the estimations for facilities across the range of production capacity, based on the assumption that emissions do not exceed the major source threshold for SO_2 (100 tpy). There are about 56 HAPs emitted by WPM, with acetaldehyde, formaldehyde, methanol, acrolein, phenol, and propionaldehyde comprising up to 90% of total HAPs. Chloride compounds (hydrochloric acid, methyl chloride, methylene chloride) account for about 2% of total HAPs. Heavy metal compounds (mercury, cadmium, nickel, lead) comprise less than 0.01% of HAPs emissions. Processes commonly associated with HAP emissions include dryer, furnace, hammer mill, and pellet storage (See S2 for more details).

For the BIOE sector, we relied upon both industry and EPA data. As of January 2022, the Biomass Magazine Biomass Power Plant dataset [63] lists 168 power plants, of which 163 facilities are operational, four facilities are under construction, and one is proposed. To identify additional facilities, we used the Emissions & Generation Resource Integrated Database (eGRID) for power generation facilities in the U.S., which EPA has maintained since 1996 [64]. Pollutants reported in eGRID are NO_X, N_2O, CH_4, CO_2, and SO_2 from the power plants and classified into biomass and non-biomass fuels. In eGRID, a fuel is classified as biomass if it belongs to the following group: agricultural byproduct (AB), black liquor (BLQ), landfill gas (LFG), municipal solid waste (MSW), other biomass gas (OBG), other biomass liquid (OBL), other biomass solid (OBS), sludge waste (SLW), wood waste liquid (WDL), and wood waste solid (WDS). Combining both BM and eGRID datasets, we identified 798 BIOEs across 48 states of which 694 facilities (87%) are included in the NEI 2017. BIOEs in the BM dataset do not include those having LFG, OBS, WDL and BLQ as feedstocks, which explains for the much lower number of BIOE in the BM than in the eGRID

dataset. Since no common metadata could be used to match BIOE from eGRID to NEI 2017, we performed spatial analyses using Geographic Information System (GIS) followed by careful name-matching to match the BIOEs. Since the energy generating capacities of BIOEs are inconsistent between BM and eGRID datasets, we relied on the capacity reported by eGRID for consistency across all BIOEs.

For the BIOEs missing from the NEI 2017, emissions of NO_X and SO_2 are taken directly from eGRID 2018 dataset. Emissions of CH_4, CO_2, and SO_2 from the eGRID dataset from both the missing and known BIOEs that share same feedstocks are used as scale factors to estimate emissions of VOC, CO, and NH_3/$PM_{2.5}$/PM_{10}, respectively, for the missing BIOEs. Given that there is only a marginal change in the number of BIOEs throughout 2016 to 2020 (Table S5), we consider that emissions estimates for BIOE are well represented for the current BIOE sources.

Only 32% of BIOEs are electricity generating facilities. The remaining BIOEs are heat generating facilities. We differentiate the electricity generating units (bEGU) and heat and non-electricity generating units (bNEGU) by their associated NAICS codes (Table S7).

We analyzed the NEI 2017 for emissions from other biomass-related combustion sources including residential wood combustion (RWC), agriculture burning, prescribed burns, and wildfires, and from all other non-biomass combustions to provide an overall comparison of emissions magnitudes from biomass vs. non-biomass sources.

Finally, we evaluated potential contribution to public health impacts of emissions from WPM and BIOE on local communities by examining distance from the facilities to the nearest populated area as a proxy. We applied the U.S. Census Bureau's criteria of defining urban areas as those with at least 1000 people per square mile [65] and calculated distances in kilometers from the facilities to the centroids of polygons depicting census blocks for year 2020 that were obtained from the U.S. Census Bureau [66].

3. Results and discussion

3.1. Emissions from biomass energy sector

Based on information from the air permits, we estimated that the 128 WPM facilities emit 6617 tpy of NO_X, 10,613 tpy of VOC, 851 tpy of SO_2, 7178 tpy of $PM_{2.5}$, and 1249 tpy of HAPs in the U.S. (Table 1, Figs. S1 and S2). Table S3 presents emissions of the above pollutants in pounds per oven-dried-ton (ODT) across five typical production capacity ranges of the WPM. As shown in Table S3, emissions rates are lower for facilities with larger production capacity. This is because larger capacity WPM facilities (typically above 100,000 ODT/yr) must be equipped with emissions control devices to keep their emissions of criteria pollutants and HAPs below major source thresholds. Minor WPM facilities,

Table 1
Annual Emissions from Wood Pellet Manufacturing Plants in the U.S. (tons per year, or tpy)[a].

State	# of Facilities	Capacity (ODT/yr)	NO_X	VOC	CO	SO_2	$PM_{2.5}$	PM_{10}	HAPs
Mississippi	6	4,900,432	1116 (±410)	1262 (±594)	1119 (±166)	179 (±45)	806 (±134)	891 (±125)	159 (±12)
Georgia	12	3,296,335	833 (±14)	1776 (±51)	888 (±24)	85 (±35)	816 (±18)	805 (±10)	119 (±3)
North Carolina	6	2,431,686	686 (±0)	583 (±0)	718 (±0)	117 (±0)	272 (±0)	375 (±0)	97 (±1)
Alabama	5	2,075,000	606 (±0)	989 (±0)	837 (±0)	76 (±4)	576 (±0)	646 (±0)	95 (±2)
Louisiana	2	1,314,823	328 (±0)	285 (±0)	181 (±0)	66 (±0)	42 (±0)	48 (±0)	21 (±0)
Virginia	10	1,175,156	435 (±56)	817 (±161)	629 (±152)	51 (±27)	549 (±146)	557 (±124)	97 (±25)
Florida	2	886,160	260 (±0)	575 (±0)	30 (±0)	31 (±3)	266 (±0)	286 (±0)	30 (±4)
Arkansas	5	799,800	276 (±0)	840 (±0)	111 (±0)	29 (±0)	240 (±51)	213 (±0)	31 (±0)
South Carolina	4	676,481	245 (±4)	496 (±25)	317 (±16)	9 (±3)	248 (±9)	258 (±5)	62 (±3)
Texas	2	536,300	232 (±0)	149 (±0)	207 (±0)	8 (±0)	62 (±0)	67 (±0)	40 (±0)
Pennsylvania	6	370,900	134 (±20)	293 (±64)	258 (±59)	17 (±12)	234 (±56)	234 (±47)	46 (±14)
New York	5	359,000	279 (±9)	285 (±88)	320 (±36)	22 (±16)	418 (±19)	406 (±11)	46 (±7)
Oregon	6	358,860	130 (±0)	371 (±0)	218 (±18)	46 (±0)	153 (±0)	171 (±0)	49 (±12)
Idaho	7	237,180	140 (±23)	229 (±76)	240 (±76)	14 (±9)	246 (±69)	236 (±61)	42 (±18)
Wisconsin	6	221,500	46 (±7)	161 (±6)	325 (±52)	7 (±5)	410 (±31)	352 (±31)	39 (±5)
Michigan	6	220,200	120 (±4)	280 (±0)	232 (±10)	0 (±0)	282 (±31)	284 (±33)	10 (±5)
Maine	4	213,300	221 (±0)	192 (±0)	453 (±0)	50 (±0)	218 (±0)	236 (±0)	69 (±7)
Others[b]	34	1,224,820	529 (±75)	1033 (±150)	1096 (±225)	44 (±19)	1339 (±324)	1379 (±304)	199 (±61)
CONUS	**128**	**21,297,933**	**6617 (± 622)**	**10,613 (± 1216)**	**8178 (± 833)**	**851 (± 177)**	**7178 (± 889)**	**7444 (± 751)**	**1249 (± 179)**

[a] Values in Table 1 were derived from the most recent air permit of the facilities which were not necessarily issued in the same year. Some permits are as recent as in early 2022 while other permits date back to 2015. Values in parentheses indicate standard error at 95 percentile confidence intervals. States with zero standard error have total emissions taken directly from issued air permits for the corresponding pollutant. States with non-zero standard error have total emissions partially or entirely interpolated from production capacity and emission rates shown in Table 1.

[b] "Others" include all states that have production capacity less than 150,000 ODT/yr. In this study, "Others" include Missouri, West Virginia, Tennessee, California, South Dakota, Washington, Colorado, Arizona, New Hampshire, Kentucky, Ohio, Alaska, Indiana, Vermont, Connecticut, Minnesota, New Mexico, Utah, Iowa, and Nebraska (ranked by most to least ODT/yr).

especially those that produce less than 10,000 ODT/yr, are exempt.

As estimated from analysis of air permits, total potential wood pellet production capacity from 126 WPM facilities in the U.S. is 21,297,933 million ODT/yr (Table S3). For comparison, Biomass Magazine [60] reports 16,074,100 ODT/yr (~24% lower) production capacity for 117 operational WPMs while EIA [67] reports 12,968,469 ODT/yr (~43% lower) capacity for 101 operational WPMs in 2021. These discrepancies could be due to several factors including validity of the air permits (many of which were issued more than five years ago) and subsequent expansions of WPM's capacity.

Annually, BIOE, comprising of electricity-generating units (bEGU) and non-electricity generating units (bNEGU), emits 296,349 tpy of NO_X, 134,286 tpy of VOC, 59,129 tpy of $PM_{2.5}$, 150,980 tpy of SO_2 and 13,538 tpy of NH_3. bEGU, comprising about 28% of total 70×10^6 MWh in 2018, contributes 28%, 4%, 16%, 25%, and 11% to the BIOE budgets of NOx, VOC, $PM_{2.5}$, SO_2 and NH_3 emissions, respectively (Table 2). Note that emissions shown in Table 2 are derived from NEI 2017 for BIOE facilities included in eGRID. eGRID shows that changes in the number of BIOE facilities and their energy generation capacity were minor in 2016, 2018, 2019, and 2020 (generation capacities are 70×10^6, 70×10^6, 67×10^6 and 64×10^6 MWh, respectively). The remaining and majority of emissions from BIOE are contributed by bNEGU which comprises about 72% of total energy generation 2018 (Table 2). State-level emissions from BIOE are presented in Table S6 for major states (those that have greater than 1.5×10^6 MWh generated from bEGU or bNEGU) and the remaining states in CONUS. Not all states have BIOE facilities as shown in Fig. 2. Energy generation capacity of bNEGU is highest in states that also lead in the production of wood pellets (e.g., Alabama, Florida, Georgia, Louisiana, Virginia).

The eGRID dataset classifies feedstocks of BIOEs into 10 categories including municipal solid waste (MSW), solid and liquid wood waste, agriculture byproducts, landfill gas, etc. Note that burning a mixture of biomass and fossil fuels in BIOE is common. Table 2 presents emissions from BIOE (bEGU and bNEGU) by fuel types as derived from NEI 2017. Non-electricity generating units (bNEGU), especially those that burn liquid wood wastes (BLQ-bNEGU), have the largest total emissions: although these facilities only generate 31% of 70×10^6 MWh total in 2018, they contribute more than 50% of each of criteria pollutants and HAPs to the total emissions from all BIOE (Table 2, Figures S3, S5 and S7). These facilities comprise sawmills, wood, and paper mills. Non-electricity generating units that burn landfill gas (LFG-bNEGU) are the second largest contributor, especially for formaldehyde (28% of the total of 3438 tpy of formaldehyde from all BIOE). BIOE with WDS fuel contributes 24% to total MWh generated from BIOE, and generally ranked as the third largest emissions contributor. WDL-BIOE has the highest emission rates of NO_X, CO, $PM_{2.5}$, and PM_{10} emissions while BLQ-BIOE has the highest emission rate of VOC, SO_2, and HAPs (Table 2). Methanol (MEOH, 66%), hydrogen sulfide (H_2S, 9%), hydrochloric acid (HCL, 8%), formaldehyde (HCHO, 4%) and acetaldehyde (ACET, 4%) are the most common HAP emissions from BIOE. LFG and WDS are the feedstocks that have highest HAP emissions (Figs. S6 and S7).

Electricity-generating units using wood waste solids (WDS-bEGU), landfill gas (LFG-bEGU) and other biomass gas (OBG-bEGU), respectively, are the top three emitters in bEGU (Figs. S4 and S6). WDS-bEGU is the top emitter of NO_X (37% of total bEGU). LFG-bEGU accounts for 65% of total VOC and 42% of total $PM_{2.5}$ emissions in bEGU. Note that 59% of WDS-BIOE are bEGU and they account for 61% of energy capacity of the bEGU sector. At a facility level, emissions (especially of VOC) from a bEGU are much lower than from a bNEGU facility, which may be due to stringent emissions control required at a bEGU facility.

Per unit of energy generated, however, facilities using other biomass liquids, gases, and solids (OBL-, OBG- and OBS-bEGU) have the highest emission rates of NO_X (39, 22, and 21 tons per 1000 MW, respectively) and SO_2 (35, 20, and 2 tons per 1000 MW, respectively) among all BIOE.

WPMs and BIOE are clustered in the Southeast, the Northeast, the Northwest, and to a lesser extent, the Upper Midwest (Figs. 1 and 2). Together, six states in the Southeast (Mississippi, Georgia, North Carolina, Alabama, Louisiana, and Virginia) account for 72% of wood pellet production in the U.S. Distributions of WPM and BIOE facilities are mainly over biomass-rich areas (biomass density greater than 50 Mg/ha as obtained from USDA [68]) as shown in Figs. 1 and 2. Among WPM, large emitters of NO_X (>100 tpy) and VOC (>300 tpy) are concentrated in the Southeast (Mississippi, Georgia, North Carolina, Alabama, Arkansas, Louisiana, and Virginia) and Pacific Northwest (Oregon, Washington) which account for more than 75% of the wood pellet production in the U.S. These states are also where the majority of large bNEGU emitters (>1200 tpy of NO_X, >1000 tpy of VOC) are found. bEGU facilities are more widely distributed across biomass-rich areas

Table 2
Emission of criteria pollutants (tons per year, or tpy) from BIOE as derived from NEI 2017.

Fuel Type	Capacity (10^3 MWh)	NO_X	VOC	CO	NH_3	SO_2	$PM_{2.5}$	PM_{10}	HAPs
bEGU									
AB	492	1986	76	1603	14	2470	186	223	52
BLQ	1492	656	24	182	37	8	14	18	15
LFG	4044	10,634	3544	27,204	154	3726	4117	4344	2039
MSW	1144	4921	67	321	141	2915	696	716	30
OBG	310	6915	538	2718	201	6223	1248	2989	110
OBL	65	2581	14	140	28	2314	135	160	0
OBS	182	3986	87	3527	151	494	459	534	1
WDS	12,018	18,961	1130	20,228	704	19,531	2899	4841	969
CONUS – bEGU	***19,748***	***50,639***	***5480***	***55,923***	***1431***	***37,679***	***9755***	***13,824***	***5480***
bNEGU									
AB	259	2923	2809	7996	223	269	702	1077	368
BLQ	25,025	164,162	97,706	182,270	8159	94,013	35,542	43,199	76,099
LFG	6291	13,217	10,235	31,571	1368	6106	6185	10,386	2603
MSW	12,897	34,201	464	6796	217	4032	1331	1563	1046
OBG	974	8093	2229	4851	937	1006	500	732	544
OBS	20	137	837	44	0	99	27	66	407
WDL	484	4387	425	3398	30	1332	1052	1530	165
WDS	5026	18,590	14,101	31,006	1174	6444	4034	6150	5997
CONUS – bNEGU	***50,976***	***245,710***	***128,806***	***267,932***	***12,107***	***113,301***	***49,374***	***64,703***	***87,229***
CONUS – BIOE	**70,724**	**296,349**	**134,286**	**323,855**	**13,538**	**150,981**	**59,128**	**78,528**	**90,446**

AB = Agricultural byproduct BLQ = Black liquor LFG = Landfill gas

MSW = Municipal solid waste *OBG = Other biomass gas* *OBL = Other biomass liquid*
OBS = Other biomass solid *SLW = Sludge waste* *WDL = Wood waste liquid*
WDS = Wood waste solid

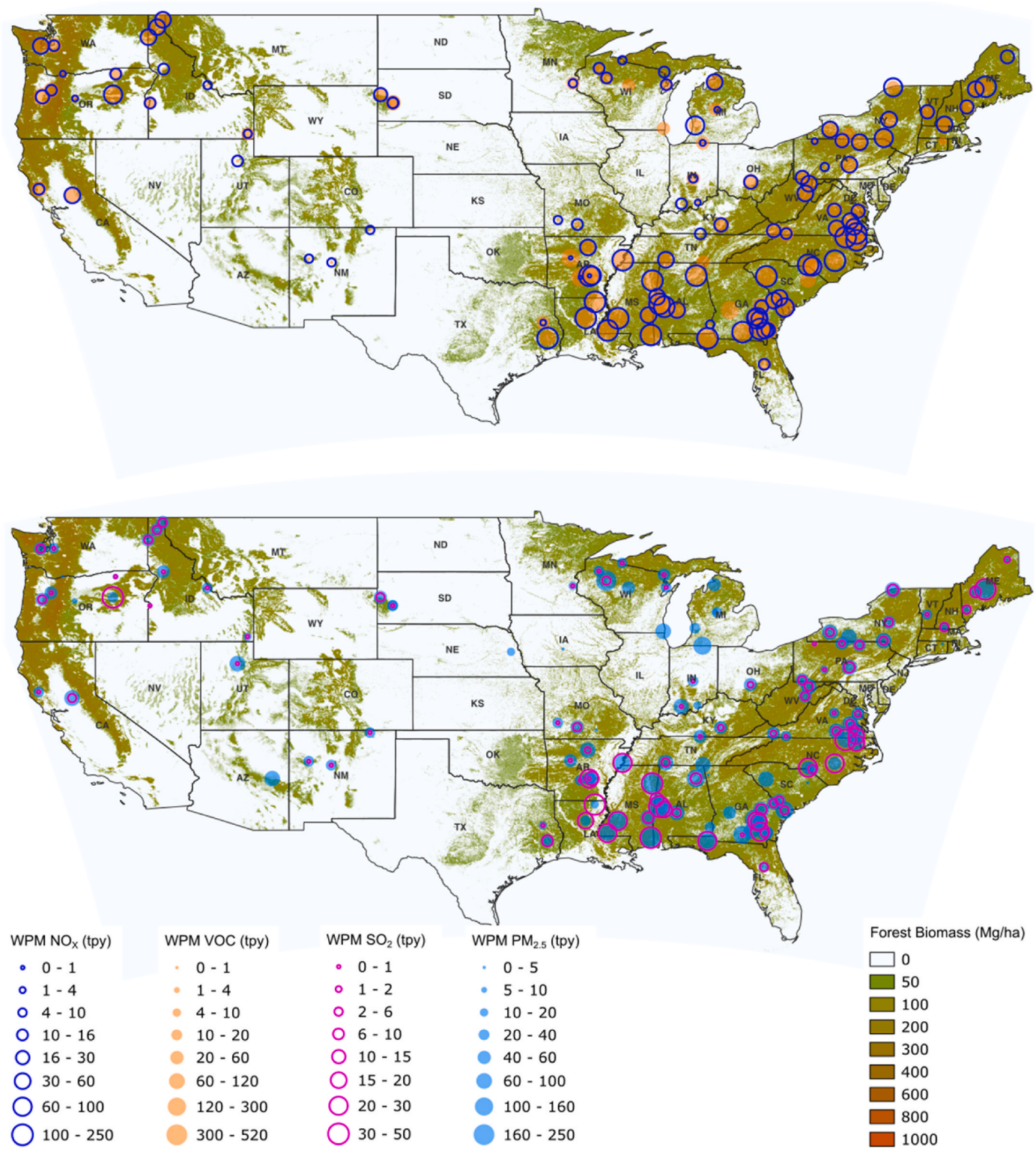

Fig. 1. Emissions of NOx and VOC (top), SO_2 and $PM_{2.5}$ (bottom) from WPM

than bNEGU, and LFG- and MSW-bEGU facilities are commonly found near urban areas (Fig. 1).

3.1.1. *Comparing biomass energy emissions with other sectors*

Finally, to facilitate comparison with other sources of air pollutants related to burning of fuels, we compiled data from NEI 2017 across multiple sectors. Note that prescribed fire and wildfires are not energy-generation related, but their emissions are presented in this study strictly for comparisons to emissions from bioenergy for perspective.

4. Discussion

Decarbonization via a transition away from fossil fuels could yield significant benefits for air quality and public health [69,70]. According to the 2023 Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC), "The economic benefits for human health from air

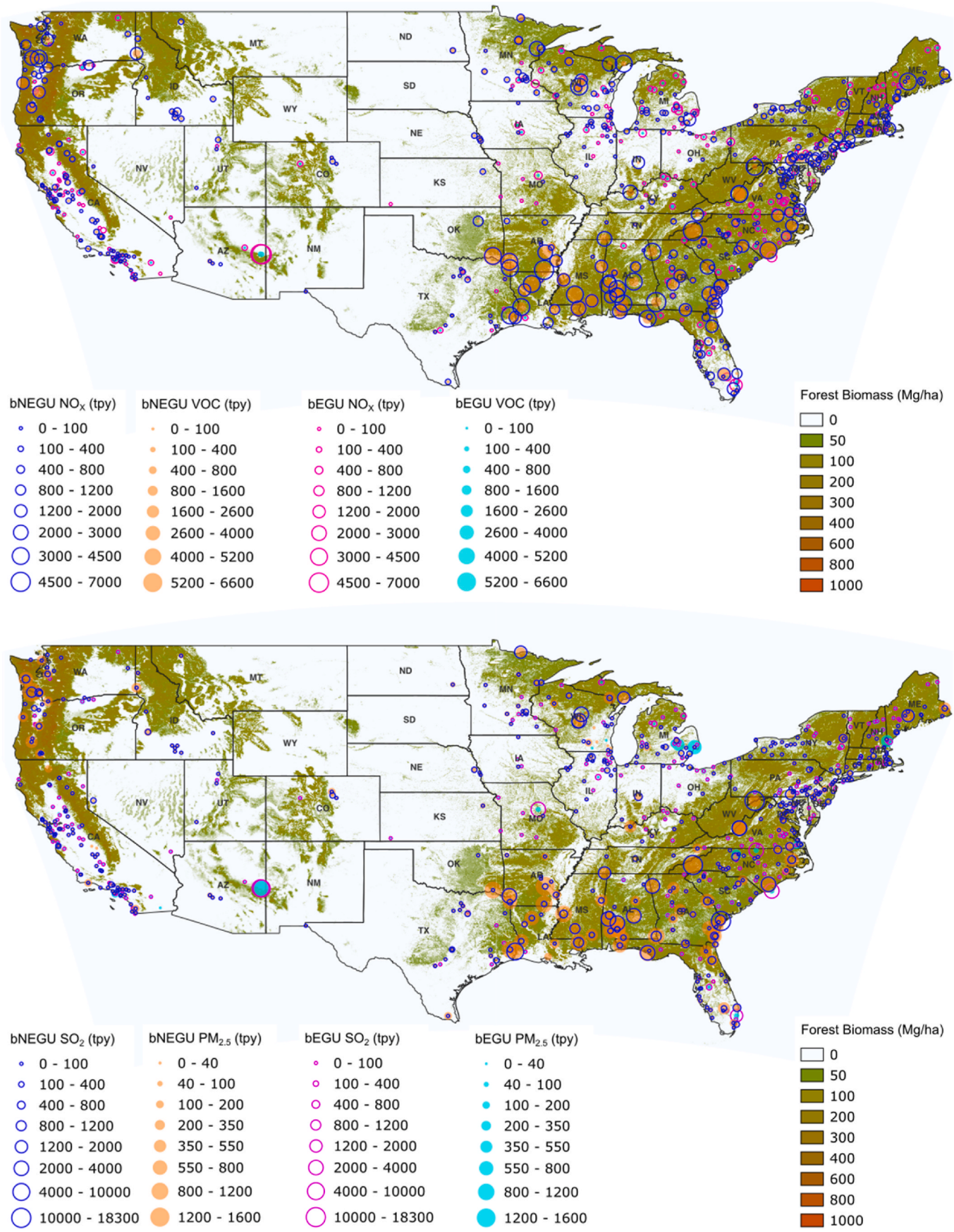

Fig. 2. Emissions of NOx and VOC (top), SO_2 and $PM_{2.5}$ (bottom) from bEGU and bNEGU in the U.S.

quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*)," [71]. Not all renewable energy sources are low- or zero-emitting, however, and if electricity generation shifts from one emissive energy source to another, these benefits to human health and cost savings may not be realized.

4.1. Comparing emissions between biomass and fossil fuels

Although total emissions from BIOE are much lower than from non-bioenergy counterparts (Table 3), BIOE emits more emissions per unit of energy generated. Among electric generating units of all fuel types, including fossil, emissions from bEGU (all feedstocks) account for 4%, 17%, 9%, 6%, 3%, 9%, and 10% of total emissions of NO_X, VOC, CO, NH_3, SO_2, $PM_{2.5}$, and PM_{10} respectively. If LFG and MSW are excluded, emission contributions from BIOE reduce to 3%, 6%, 5%, 5%, 2%, 4%, and 6% respectively. Generation capacity of bEGU, however, only accounts for about 1% of total capacity from the electric generation sector. Accounting for 30% of generation capacity, bNEGU contributes 17–28% of total emissions of criteria pollutants from non-electricity generating energy (all fuel types, including fossil) (Table 3). Comparisons of emissions from BIOE to other anthropogenic emissions are presented in Figs. S8 and S9.

To quantify and compare across different emissions sources, we can also consider emissions intensity (EmI), defined in units of tons per 10^3 MWh. EmI of NO_X, VOC, NH_3, SO_2, and $PM_{2.5}$ from bEGU are 2.6, 0.3, 0.07, 1.9, and 0.5, respectively, which are substantially higher than those from NonBio (i.e., fossil) EGU which are 0.5, 0.01, 0.01, 0.6, and 0.04, respectively, and range between 217 and 2900% depending on pollutant. The corresponding EmI from bEGU excluding LFG and MSW feedstock are 2.4, 0.1, 0.08, 2.1, and 0.3, which are also higher than those from NonBio EGU by between 250 and 900%. bNEGU, including all feedstock, have comparable emissions per MWh generated to NonBio NEGU. However, if LFG and MSW feedstock are excluded, bNEGU's EmI of NO_X, VOC, NH_3, SO_2, and $PM_{2.5}$ are 3.4, 2.0, 0.18, 1.7, and 0.7 which are relatively higher than those from NonBio NEGU (1.8, 1.8, 0.14, 1.4, and 0.5, respectively) by between 11 and 89%.

4.2. Understanding WPM estimates

WPM facilities with large production capacity (typically above 100,000 ODT/yr) are required to install and operate emissions control devices properly to keep emission rates below major source thresholds. However, such obligations are not always met. As mentioned above, the NEI 2017 dataset shows that the annual emissions of 16 of the 42 WPM facilities exceed the common threshold (i.e., 250 tpy) for major sources, which indicates that sufficient emission controls were either not in place or not operated properly. Emissions from the 42 WPM facilities included in NEI 2017 are about 1.2–1.7 times higher than the emissions derived from air quality permits across criteria pollutants (Table S4). On the other hand, total emissions from WPM estimated from this study are 1.1–2.2 times higher than in the NEI 2017 across criteria pollutants as more facilities are considered (128 facilities).

Moreover, violations of air quality permits by WPMs have been documented. Facilities in Georgia, North Carolina, Alabama, Mississippi, South Carolina, and Texas reported at least 18 violations, with several facilities repeatedly violating their permit limits and total penalty amounts exceeding $7 million [72]. Several facilities were repeat offenders, including facilities with production capacity larger than 500, 000 ODT/yr. For example, all three violations by Texas WPMs were committed by the same facility. An industry watchdog report by the Environmental Integrity Project [73] found that 7 out of 21 WPMs in the Southeastern U.S. that export to Europe committed emission violations in 2017, and 11 of the 21 either failed to keep emissions below legal limits or failed to install required pollution controls. In 2021, a WPM facility in Gloster, Mississippi was awarded a fine of $2.5 million for excessive VOC emissions [74]. In 2022, the owner of two additional WPM facilities owned in Bastrop and Urania, Mississippi agreed to pay fines of $1.6 million per facility for additional alleged violations, including VOC levels around 1100 tpy (more than 400% of the permitted limit of 250 tpy) [75,76].

Given the frequent emission violations of WPM in the past and our reliance on data reported in permits, our study likely underestimates the actual emissions from many WPM facilities. For example, our total estimate for VOC emissions from Mississippi is 1262 tpy (Table 1) with VOC emissions from the last two aforementioned facilities less than 200 tpy each. The above discrepancies suggest that emissions from WPM in this study could be underestimated by an approximate factor of 1.5–3.

4.3. Potential for inequitable impacts

Although biomass pretreatment and bioenergy deployment may be motivated by interest in decarbonization, each could have impacts on air quality and public health. Increases in utility-scale bioenergy or large-scale pellet production could delay relief of air pollutant exposures in overburdened areas. Residential wood-burning stoves may also present concerns for environmental justice. Estimates suggest between 0.5 million to 4.8 million vulnerable individuals (i.e., low-income, children, and the elderly) are at risk for adverse health effects related to wood smoke exposure within their homes [77,78], and wood smoke is also a cause of non-attainment of PM standards in some areas, potentially exacerbating pollutant burdens [37].

While domestic use of commercial-scale bioenergy in the U.S. remains relatively low, both wood pellet production plants and large-scale bioenergy generation facilities in the U.S. have been met with resistance from members of affected communities, such as Springfield, MA [79];

Table 3
Emissions (tons per year, or tpy) from various combustion source groups over CONUS.

	Capacity (x 10^3 MWh)[c]	NO_X	VOC	CO	NH_3	SO_2	$PM_{2.5}$	PM_{10}
RWC[a]	N/A	34,094	323,682	2,160,536	16,408	7988	299,279	300,140
WPM	N/A	6699	10,653	8230	NA	861	7331	7605
bEGU[b]	19,748 (14,560)	50,639 (35,085)	5480 (1868)	55,923 (28,398)	1431 (1136)	37,679 (31,039)	9755 (4941)	13,824 (8764)
bNEGU[b]	106,112 (58,694)	245,710 (198,293)	128,806 (118,107)	267,932 (229,565)	12,107 (10,523)	113,301 (103,163)	49,374 (41,857)	64,703 (52,754)
NonBio EGU	2,299,222	1,129,739	26,548	553,179	21,344	1,362,669	102,119	122,482
NonBio NEGU[1]	348,282	626,652	618,425	1,084,767	48,624	471,545	193,276	315,531
Agriculture Fires[a]	N/A	15,907	45,292	359,379	86,695	6069	29,171	47,295
Prescribed Fires and Wildfires[a]	N/A	357,178	5,555,642	23,817,819	389,528	186,731	2,087,231	2,460,819

[a] RWC*: Residential Wood Combustion; Agriculture Fires*: grass and agriculture fires; *Prescribed Fires and Wildfires*: controlled fires and wildfires; *NonBio* EGU: non-biomass burning electric generating point sources (ptegu in the NEI less bEGU); *NonBio* NEGU: non-biomass burning and non-electric generating sources (ptnonipm in the NEI less bNEGU*)*.

[b] For bEGU and bNEGU, values in parentheses are for when LFG and MSW feedstocks are excluded from bEGU and bNEGU for emissions accounting.

[c] Generation capacities taken from eGRID dataset; NonBio EGU exclude generation capacity from geothermal, hydro, solar, wind and nuclear power plants.

Adel, GA [80]; Flint, MI [81]; and others (e.g., Refs. [82,83]). In the Southeastern U.S., wood pellet plants have been disproportionately sited in environmental justice communities [84], which are communities that are overburdened with environmental hazards and that have increased vulnerability to these hazards, due to race, socioeconomic status, or other factors. Incinerators of MSW have generated local opposition and controversy for decades, particularly in relation to emission of dioxins [85,86] and discriminatory siting practices, and have been the subject of scholarship at the intersection of renewable energy and environmental justice [87]. WPM facilities may also increase pollutant burdens in environmental justice communities as the result of fugitive dust and tailpipe emissions, including PM related to increased vehicle traffic to and from the facility, which community members have identified as key concerns (e.g., see Ref. [88]).

As shown in Tables S8 and S9, the average distance from a WPM or BIOE facility to nearest urban area is approximately 2 km and the total population within ~2 km and ~5 km of either WPM or BIOE facility amounts to about 2.3 million and 14.4 million people, respectively, in the U.S. Many WPM and BIOE are sited in the immediate proximity of urban areas. Just under half of WPM and BIOE are within 1 km of an urban area. Given their close vicinity to the populated areas and magnitude of their emissions, the WPM and BIOE facilities identified in this study pose potentially significant health impacts to local communities. Future studies that perform full chain health impact assessments using comprehensive emissions and air quality modeling of these facilities may be warranted, similar to recent studies (e.g., Refs. [89,90]) for other emissions sectors like on-road and air transportation.

Polluting facilities have impacts both near and far. For example, large EGUs, including those that may co-fire biomass in addition to coal, may emit pollutants into the atmosphere that may travel long distances, and on average, as much as 53% of premature mortality in a given state may be related to pollution originating in another state [50].

4.4. Future year projection of WPM and BIOE and associated health impacts

As of 2019, biopower from wood and waste energy represented 24% of total U.S. renewable energy consumption [12]. Around 4835 trillion BTU units of energy derived from biomass were consumed in the U.S. in 2021, which is a slight decrease from its peak of 5105 trillion BTU in 2018 [67]. Residential consumption has fluctuated, from 579 trillion BTU in 2014 to 464 trillion BTU in 2021, while consumption by the industrial sector has remained fairly constant in the last decade, consuming 2313 trillion BTU in 2021 [67]. In terms of installed biopower electricity capacity, Florida leads the way (1416 MW), followed by California (1394 MW), and Virginia (1018 MW) [91]. In 2021, approximately 37.3 billion kilowatt hours (kWh) of electricity were generated from wood and wood-derived fuel, an increase from 2001 (35.2 billion kWh) but a slight decrease from its peak in 2014 (42.3 billion kWh) [67]. According to EIA's Wood and Biomass Waste Consumption Estimates 2020, Georgia was the largest consumer of wood and biomass waste in the U.S. in 2020 (208.2 trillion BTU), followed by Alabama and California (160 and 148 trillion BTU, respectively) [12]. Georgia also leads consumption in the industrial sector, followed by Alabama and Louisiana [12].

While emissions from BIOE in the U.S. are expected to stay constant from 2022 to 2025, emissions from WPM, could be expected to increase as global demand grows, demand for wood pellets is projected to grow significantly in the coming decades, with the Southeastern U.S. in particular remaining a major producing region [16, 92]; see also S1. From 2018 to 2022, wood pellet production in the Southeastern U.S. increased from 9.3 million tons to 10.5 million tons whereas production (2.8 million tons in 2022) in the remaining regions was fairly stable [67]. There are five proposed or prospective WPM facilities with production capacity between 500,000 and 1,000,000 ODT/yr each in Mississippi, Alabama, Virginia, and South Carolina, which will export pellets to Europe [93]. Export of wood pellets have increased in the past five years, reaching 8.8 million tons ($1.7 billion) in 2022 [67]. Domestic sales of wood pellets, on the other hand, slightly decreased in the same past five years (2.1 million and 1.8 million tons in 2018 and in 2022, respectively).

Residential and district-scale thermally-led bioenergy production may remain integral to energy security and the health of local economies in some regions of the U.S., particularly in isolated areas and those with cold climates – in other words, in some contexts, the benefits to local economies and to energy independence may outweigh the costs [94]. Nonetheless, air pollution from residential wood-burning stoves poses significant risks to public health and should not be overlooked [37].

Analysis published in 2017 found that around 10,000 premature deaths annually in the U.S. may be attributable to emissions from RWC [48]. Increased use could increase those estimated impacts. For example, from the 2017 NEI to the 2020 NEI [95], $PM_{2.5}$ emissions from RWC increased 44%, while NO_X emissions increased 27%.

Emissions from prescribed fires and wildfires clearly represent a serious threat to air quality (Table 3). Considering increasing intensity of wildfires and duration of fire seasons, these impacts may become more pronounced in the coming years. Already, around 4000–9000 deaths per year may be attributable to wildfire-induced PM concentrations in the U.S [96]. We compare these figures to premature mortality attributable to pollutant emissions from the electricity generation sector across the country (e.g., 4000–9000 deaths per year, [49,50]; 21,000 deaths per year, [48]).

Collecting materials from fire-prone forests for bioenergy has been identified as a possible solution to offset costs from forest management and reduce fire hazards. Proponents of large-scale electricity generation may argue that open-burned biomass emissions often far exceed those of utility-scale plants and even residential stoves, and that combustion of woody materials in a plant with pollutant control technology is thus preferable to burning in forest or field (e.g., Refs. [97,98]). Nonetheless, burning – with either abated or unabated emissions – is not the only possible fate of biomass "wastes" and "residues" removed from forests. Alternatives for valorization of biomass wastes, forest thinnings, and residues continue to multiply and mature. These include uses in bioplastics [99], biochemicals and nano materials [100], biochar [101], sustainable aviation fuels [102], mass timber [103], and building materials such as wood fiber insulation [104], in addition to traditional applications such as oriented strand board [105]. Given the declining costs of clean, non-emitting energy sources such as solar photovoltaic [71], projected growth in global demand for wood products [106], and air pollutant emissions associated with bioenergy generation described here, such non-energy alternatives merit robust evaluation by policymakers. Given the growing suite of threats to human health posed by climate change, decarbonizing using clean energy sources is increasingly imperative [69].

4.5. Limitations of this study

Emission factors vary both between and among biomass feedstocks (as the result of variation in chemical composition, size, and moisture content) and are also influenced by combustion technology and conditions (including the ratio of oxygen to fuel) [33,39]. Impacts of various combustion techniques were not considered in this study, though such impacts have been studied extensively, especially in residential combustion (e.g., Refs. [107,108]). Although we discuss emissions from various BIOE feedstocks, there is still insufficient information in the NEI to estimate emissions rates for specific feedstocks. For example, NEI does not distinguish between wood type (e.g., dry vs. wet) in WDS fuel, and further does not provide specific sub-categories for AB. Wood species and moisture content may greatly affect emissions from wood combustion [109] but such factors are beyond the scope of this study.

From our study, we derived median emission factors of 0.92 ± 0.27 lb/MMBTU of VOC, 2.33 ± 0.59 lb/MMBTU of NO_X, 0.64 ± 0.24 lb/

MMBTU of $PM_{2.5}$ for WDS-BIOE. The median emission factors of these pollutants are 0.06, 0.8, and 0.242 lb/MMBTU, respectively, indicating skewed distribution toward large emitters; a similar distribution was also reported in Ref. [33]. These factors are slightly higher than the AP-42 emission factors for residual wood combustion (median 0.017 lb/MMBTU of VOC, 0.22–0.49 lb/MMBTU of NO_X, and 0.31–0.43 lb/MMBTU of $PM_{2.5}$) and those reported by Bhatt et al. [33]; however, we attribute the discrepancies to the fact that the emission factors in this study were estimated on an annual basis and over a large number of facilities, whereas emission factors in the above comparison dataset are developed from instantaneous and limited number of measurements.

Only 42 of the WPM facilities included in industry databases could be identified in the current NEI 2017. Emissions from those WPM facilities as derived from NEI 2017 are higher than emissions derived from this study from the same facilities (Table S4). Discrepancies in reporting year (i.e., earlier than 2017 for the NEI 2017 and later than 2017 for this study) and in calculation methods are the main reasons for the differences between the two datasets. Furthermore, many WPM facilities made modifications to their production line after 2017 as indicated in their latest permits. The air permits used in this study were issued in different years over the last 10 years. The temporal mismatch issue of WPM's emissions should be considered when applying the data in modeling applications for a particular base year.

Finally, we note that this study does not account for emissions from other sectors in biomass energy and in the supply chain, including harvesting and transportation of feedstocks to WPM facilities and transportation and distribution of products from the WPM facilities to end use (residential, industrial, BIOE).

5. Future perspectives

Although deployment of utility-scale bioenergy in the U.S. remains low, global demand for densified biomass continues to grow, as does domestic interest in both alternatives to fossil fuels and useful applications for wastes and materials from hazardous fuel removals in landscape management. Bioenergy deployment has been embraced as an element of the transition away from fossil fuels and by those who value energy independence. However, both biomass pretreatment and bioenergy generation can deteriorate air quality. The emissions datasets developed from this study could be utilized in a comprehensive health impacts assessment framework that relies on a comprehensive modeling framework (such as WRF-SMOKE-CMAQ-BenMAPR) that has been used in multiple studies (e.g., Refs. [89,90]) to evaluate bioenergy's impacts on air quality and public health in the U.S., in terms of public health costs that include morbidity and mortality-based endpoints.

Although virtually every energy source presents trade-offs, the literature review and the new emissions inventory presented here suggest that an overreliance on bioenergy at several scales could have the potential to delay or offset progress toward improved air quality afforded by the transition away from fossil fuels, to perpetuate legacies of environmental injustice (resulting from co-firing with coal and fuel switching in historically overburdened areas and "sacrifice zones"), and to displace cleaner and increasingly more affordable alternative energies, from solar panels to heat pumps. For example, a U.S. decarbonization policy that reduces CO_2 emissions by 50% may reduce $PM_{2.5}$ related health benefits across the board but may also increase the average exposure disparity for racial/ethnic minorities from 12.4% to 13.1% [55]. We encourage policymakers and decision makers to rigorously assess the potential health co-benefits (or disbenefits) of climate mitigation and adaptation strategies, in addition to the greenhouse gas outcomes. As the authors of a previous study noted, "swapping one air pollution-emitting fuel source for another is not a pathway to a healthy energy system," [51].

6. Conclusions

We have quantified emissions from major source types in the bioenergy sector including RWC, WPM, and BIOE. We developed a bottom-up approach that is based on analyses of regulatory permit applications and quantified the emissions magnitudes for various types of bioenergy for different pollutants, and how they compared with the EPA's NEI estimates. Our findings suggest that the emissions from this growing sector may be significantly underestimated in the current NEI 2017, especially for WPM and identify specific areas for improvement. Emissions from BIOE are estimated separately from their non-bioenergy counterparts. While total emissions from BIOE are lower than those from non-bioenergy, BIOE emit more pollutants per unit energy generated than from non-bioenergy sources. Our findings have significant implications on potential burdens on air quality and human health due to the transition from traditional fossil fuel to presumed "carbon neutral" biomass fuel. Although bioenergy still represents only a small portion of total energy generation in the U.S., policymakers should consider the adverse implications of scaling up due to energy demand, or even due to economic reasons.

CRediT authorship contribution statement

Huy Tran: Methodology, Writing – original draft, preparation, Data curation, Visualization. **Edie Juno:** Writing – original draft, preparation, Writing – review editing. **Saravanan Arunachalam:** Methodology, Writing – review editing, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.119536.

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