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Estimating avoided fossil fuel emissions from U.S. woody biomass energy use, 1949–2024

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ABSTRACT

Understanding fossil fuel displacement benefits of wood energy use is essential for tracking national forest-sector sustainability metrics. Using a cradle-to-gate life cycle assessment (LCA) approach, this study presents a transparent and replicable framework to estimate the avoided GHG emissions associated with wood energy use across the residential, commercial, industrial, and electric power sectors from 1949 to 2024. The results show wood energy use is estimated to have cumulatively avoided 13,545 million tonnes CO_2e, and 111 to 243 million tonnes CO_2e annually between 1949 and 2024, representing about 2.5 to 3% of total U.S. annual CO_2e emissions between 1990 and 2022. The magnitude and temporal pattern of avoided emissions over the years reflect the combined influence of shifts in sectoral wood energy usage and fossil fuel mixes. For instance, residential wood energy share declined by 47%, in 2024 while industrial, electric-power, and commercial shares increased by 37, 8.5, and 2.5%, respectively, relative to 1949. Over this same period, the U.S. energy system transitioned from a coal-dominated fossil-fuel mix toward increasing reliance on natural gas and petroleum products. Despite limitations such as proportional fossil-fuel displacement assumptions, lack of facility level fuel-use data, and fixed life cycle emission factors, the transparent and replicable LCA-based framework presented in the study enhance understanding of wood energy's role in national carbon-mitigation efforts. It also directly supports U.S. forest sector sustainability reporting under Montréal Process Criterion 5, Indicator 5.24, which addresses avoided fossil fuel carbon emissions by using forest biomass for energy.

1. Introduction

U.S. is the world's largest producer of industrial roundwood [1,2]. While long-lived wood products are primary drivers of economic value in the forest products sector, woody biomass has also played an important role as a renewable energy source. Wood and wood-derived fuels, such as pellets, cellulosic ethanol, and sustainable aviation fuels, are increasingly being positioned as a key component of the U.S. energy strategy that aims to improve energy security, boost local economies, and protect the environment [3]. Although the renewable energy portfolio has diversified substantially over past decades, wood energy remains the second-largest renewable energy source in the country [4]. Its share in U.S. renewable energy declined from more than 80% in 1950 to about 21% in 2024, yet absolute consumption increased from 1.55 to 1.81 quads during the same period [4]. Sustainably managed forests in U.S. can support a continuous supply about 22 million dry tons woody biomass per year for energy from logging residues and small trees in near term, reinforcing the contribution of wood to the nation's renewable energy portfolio [5].

Historically, woody biomass was predominantly used for residential heating, with a gradually increasing share directed toward industrial heat and electricity generation [6–8]. Understanding these long-term patterns is essential not only for evaluating the contribution of wood energy to fossil fuel emissions mitigation, but also for tracking national forest sustainability and meeting international reporting requirements [9]. Although previous studies have examined specific components of historical wood energy use, they have not provided a comprehensive national-level assessment of how wood energy has contributed to fossil fuel displacement over time. Song et al. [8] documented declining residential wood energy consumption from 1967 to 2009 driven by the greater availability of alternative energy sources, technological improvements, affordability, and urbanization [8]. Other studies have assessed environmental implications of woody biomass utilization in specific regions [10,11]. However, national scale, long-term assessments

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of fossil fuel displacement from wood energy remain limited. In a recent study, Taylor et al. [12] estimated national substitution impacts for harvested wood products using product-specific displacement factors and fixed end-use allocations applied across reporting years [12]. In their analysis, substitution impact of harvested wood products used for energy (energy wood, pellets, and solid waste incineration) totaled 29 Tg CO_2e in 2020, based on an average displacement factor of 0.68 derived from a study conducted within the Canadian context [13]. The value reflected substitution within harvested wood product flows rather than fossil fuel displacement from U.S. wood energy consumption across residential, commercial industrial, or electric-power sectors. This distinction underscores a key gap addressed in the present study i.e. quantifying annual fossil fuel displacement from wood energy use using sector-specific fuel mix allocations and displacement factors estimated for U.S. context. This study provides the first national-scale, sector--specific assessment that integrates historical fossil fuel mixes with life cycle assessment (LCA) based framework to quantify avoided fossil emissions from wood energy use over a 76-year period.

A major motivation of this study is to strengthen U.S. forest sector sustainability reporting under the framework of Montréal Process Criteria and Indicators [14]. As a signatory, the U.S. follows a standardized framework for assessing national progress in sustainable forest management [15]. This framework consists of seven criteria, each addressing a distinct aspect of forest sustainability. Criterion 5 focuses on maintaining forest contribution to global carbon cycles and indicator 5.24 specifically tracks: (1) the amount of energy produced from forest biomass and (2) fossil fuel carbon emissions avoided through forest biomass energy substitution [9]. These metrics highlight the role of forests as both carbon sinks and renewable energy resources that contribute to national carbon mitigation. However, the past U.S. sustainability indicator reports have quantified emissions from wood energy consumption [9], but have not estimated the corresponding avoided fossil fuel carbon emissions, leaving an important gap in national sustainability assessment and reporting [15]. While the U.S. Energy Information Administration (EIA)'s reports sectoral GHG emissions [4], biogenic emissions from biomass combustion are treated carbon neutral and are either excluded or reported separately [4,16,17]. The U. S. Forest sustainability reporting remains incomplete without quantifying the extent to which fossil fuel carbon emissions are reduced because of wood energy substitution. This study fills that gap by introducing a LCA based framework to estimate the avoided fossil fuel emissions attributed to historical use of biomass for energy in the United States.

Recent federal guidance, such as chapter 5 of USDA's Methods for Quantifying GHG Fluxes in Managed Forest Systems [18], offers a first order general approaches for estimating substitution benefits from wood fuels, relying on broad assumptions about fossil energy sources, and therefore does not provide a framework suitable for national level assessment. Similarly, national GHG emissions inventory reports published by the U.S. Environmental Protection Agency (EPA) follow Intergovernmental Panel on Climate Change (IPCC) guidelines for accounting carbon stock changes and non-CO_2 emissions across land-use and land-use change categories [19]. However, they do not include the quantity of biomass energy used or fossil fuel emissions avoided from biomass energy substitution. In contrast, Indicator 5.24 seeks a life-cycle perspective that encompasses both wood energy production and fossil fuel emissions avoided, providing a more comprehensive view of the carbon mitigation benefits of forest-based energy systems [14]. As such, Indicator 5.24 could complement EPA's national GHG reporting framework by specifically tracking the quantity of forest biomass utilization and corresponding carbon mitigation benefits resulting from substitution of fossil energy [15].

Therefore, the goal of this study is to develop reproducible LCA-based framework for estimating avoided fossil fuel emissions associated with historical U.S. wood energy use. The study contributes both to national forest-sector sustainability assessments and reporting and discussions on the role of biomass in long-term climate-mitigation strategies. The study conducts a long-term, 76-year assessment of (1) the wood energy consumption across the residential, commercial, industrial, and electric power sectors from 1949 to 2024, (2) the quantity of fossil fuel displaced by wood energy based on sector-specific fossil fuel mixes, and (3) the associated annual and cumulative reductions in GHG emissions over this period. Ultimately, the study offers important insights for stakeholders seeking to understand both the evolving role of woody biomass in U.S. energy generation and its contribution to national carbon mitigation goal, while enhancing forest sustainability reporting efforts.

2. Methodology

Fig. 1 outlines the methodological framework used in the analysis. Three primary datasets form the foundation of the analysis: (1) U.S. historical wood energy consumption, (2) U.S. historical fossil energy consumption, and (3) cradle-to-gate life cycle GHG emissions for each energy source. Using these inputs, we evaluated historical changes in wood energy use across four sectors: residential, commercial, industrial, and electric power and estimated associated reductions in fossil fuel emissions resulting from the displacement of fossil energy by wood energy over time. The data and analytical procedures used in the framework are described below.

2.1. Data sources

Historical U.S. woody biomass and fossil energy consumption data for four primary wood energy consuming sectors (residential, commercial, industrial, and electric power) are compiled from the U.S. EIA Monthly Energy Review report [4]. Table 1 lists the specific data used from this report. The energy consumption data was reported in quadrillion British thermal units or quads, where 1 quad = 10^{15} British thermal units. Using these data, we estimated annual fuel mixes by calculating the % shares of wood and fossil fuels in total energy consumed (Table S1a–d). These sector-specific fuel mix allocations provided a consistent basis for assessing how wood energy use has shifted over time and identifying the equivalent fossil fuel mix displaced each year.

2.2. GHG emissions from wood and fossil energy use

The production and use of wood fuels (e.g., logs, chips, pellets) require some fossil energy inputs in the operations such as harvesting, hauling, processing, chipping, and drying, each of which generates associated fossil GHG emissions. Fig. 2 shows the system boundary used to estimate these emissions for both wood fuels and fossil fuel energy systems, consistent with LCA framework outlined in ISO 14040 and ISO 14044 [20,21]. Within this boundary, only fossil-derived emissions are counted for wood-energy pathways; biogenic carbon uptake and release are excluded. This treatment of biogenic carbon is consistent with the widely accepted assumption that, at the landscape scale, sustainably managed forests maintain a long-term balance between carbon sequestration through growth and carbon emissions from combustion of biomass [4,16,17]. A detailed accounting of biogenic carbon uptake and release is considered appropriate when the goal is to evaluate net carbon mitigation benefits at the specific project level or over a shorter time period [22].

The GHG emissions associated with use of wood energy in the U.S. were estimated in kilograms of CO_2 equivalents per MJ of heat and electricity. The cradle-to-gate GHG emissions per MJ of wood energy were quantified using the LCI processes from USLCI and DATASMART databases [23] in SimaPro 9.6 software [24] and with U.S. based TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) method [25]. Table 2 lists the LCA processes used and quantified GHG emissions per MJ of energy. For heat energy, the GHG

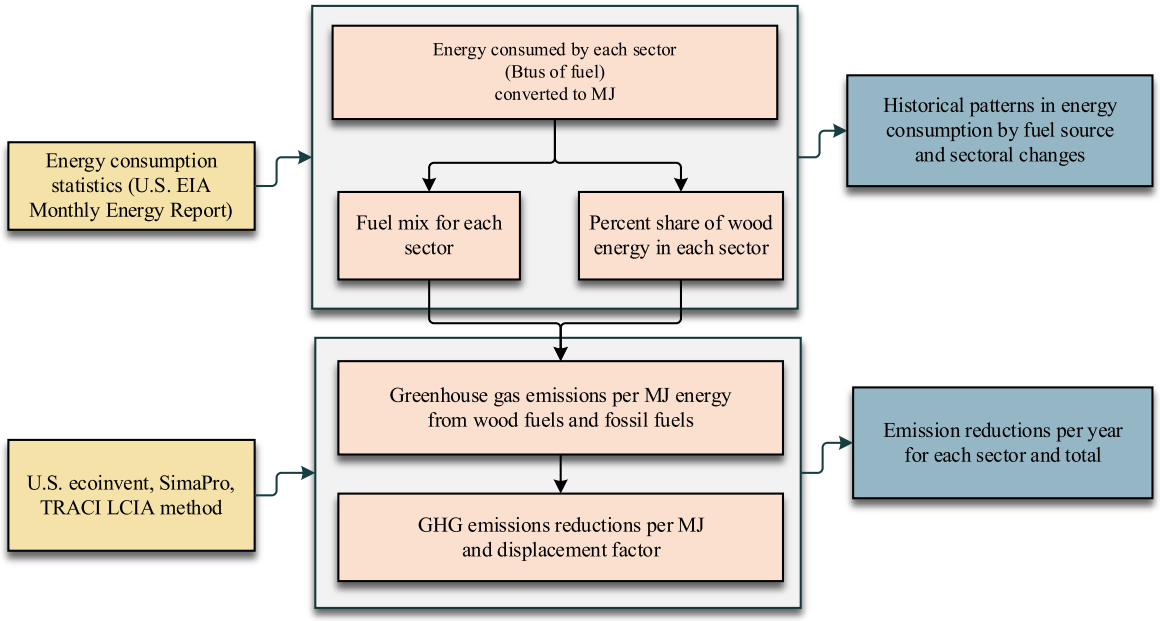


Fig. 1. Methodological framework applied in the study to estimate avoided fossil emissions from wood energy use in the United Sates.

Table 1
Sector specific U.S. energy consumption data used in the analysis, 1949 – 2024. Source: Monthly Energy Review [4].

Data Table	Description
Table 2.1a, Table 2.1b	Total energy consumption by the residential, commercial, industrial, and electric power sectors
Table 2.2, Table 10.2a	Residential sector energy consumption by fuel type
Table 2.3, Table 10.2a	Commercial sector energy consumption by fuel type
Table 2.4, Table 10.2b	Industrial sector energy consumption by fuel type
Table 2.6, Table 10.2c	Electric power sector energy consumption by fuel type

emissions of wood fuels were estimated as the average of emissions from wood logs, wood chips, and wood pellets. Because the emissions intensity of pellets differed substantially from that of wood logs and chips, using a value for one single fuel type would not adequately represent the range of wood-based energy systems used in practice. To better capture this variation, we therefore used an average emissions intensity value across logs, chips, and pellets rather than selecting only one wood fuel type. This averaging approach provides a more representative characterization of wood-energy emissions within the national historical context and ensures consistency when comparing wood-energy displacement effects against fossil-energy sources.

For fossil fuels, cradle-to-gate GHG emissions per MJ were estimated for coal, natural gas, and fuel oil using the USLCI and DATASMART databases and TRACI methods in a similar manner. As shown in Table 2, the GHG emissions from 1 MJ of fossil fuels energy are considerably higher than the equivalent amount of wood fuel energy. The difference between the GHG emissions of wood fuels and those of fossil fuels represents the emissions reduction benefits (avoided fossil emissions) achieved when wood displaces fossil energy. This difference in GHG emissions forms the basis for calculating annual fossil emissions reductions attributable to wood energy use over time.

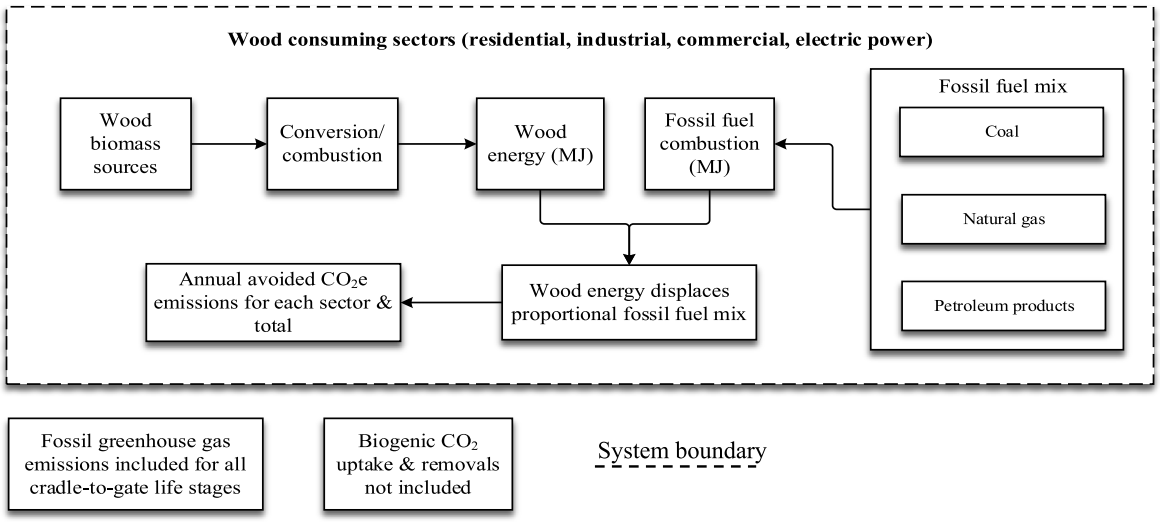


Fig. 2. System boundary applied in the cradle-to-gate LCA of wood and fossil fuels.

Table 2
LCA processes used and GHG emissions per MJ of energy.

Fuel type	kg wood combusted/MJ	GHG emissions (kg CO_2 e/MJ)	LCA process
Heat			
Coal		0.110	Heat, at hard coal industrial furnace 1-10MW/US- US-EI U
Natural gas		0.079	Heat, natural gas, at industrial furnace >100kW/ US- US-EI U
Fuel oil		0.092	Heat, light fuel oil, at industrial furnace 1MW/US US-EI U
Hardwood logs	0.045	0.008	Logs, hardwood, burned in furnace 30kW/US US-EI U
Hardwood logs	0.045	0.008	Logs, hardwood, burned in furnace 100kW/US US-EI U
Mixed logs	0.047	0.004	Logs, mixed, burned in furnace 30kW/US US-EI U
Wood chips, forest	0.132	0.010	Wood chips, from forest, softwood, burned in furnace 50kW/US US-EI U
Wood chips, industry	0.125	0.005	Wood chips from industry, softwood, burned in furnace 50kW/US US-EI U
Wood pellets	0.032	0.020	Pellets, mixed, burned in furnace 50kW/US US-EI U
Electricity			
Coal		0.307	Electricity, hard coal, at power plant/US US-EI U
Natural gas		0.200	Electricity, natural gas, at power plant/US US-EI U
Fuel oil		0.241	Electricity, residual fuel oil, at power plant/US
Woody biomass	0.128	0.013	Electricity, biomass, at power plant NREL/US U [11],

2.3. Framework for estimating fossil fuel displacement and avoided fossil emissions

This section describes a reproducible LCA-based framework we applied to quantify fossil fuel GHG emissions avoided through historical wood energy use in the United States. The framework integrates annual sector-level wood energy consumption and observed proportions of fossil fuel mixes to estimate average fuel-specific displacement factors (DFs). These DFs then allowed estimation of avoided fossil emissions across four wood energy consuming sectors. Key elements and underlying assumption in this framework are described below:

2.3.1. Proportional fossil fuel displacement

Sectoral energy consumption data from U.S. EIA provide annual consumption of coal, natural gas and petroleum products but do not include facility-level or technology-specific information to model displacement benefits at finer operational scales. Therefore, sector-specific wood energy use is allocated proportionally across each sector's fossil-fuel mix, to estimate the amount of each fossil fuel type displaced by wood energy each year. If a sector s uses $W_{s,t}$ wood energy (MJ) in year t, and fossil fuel type f represents a proportion $P_{s,f,t}$ of sector's fossil fuel mix in that same year, then the amount of displaced fossil fuel energy of type f (MJ) in sector s is estimated according to equation (1).

$$\text{Displaced fossil energy } (DQ_{s,f,t}) = W_{s,t} \times P_{s,f,t} \quad \text{Eq. 1}$$

where, $W_{s,t}$ is the amount of wood energy consumed (MJ) in sector s (residential, commercial, industrial, electric power), in year t *(1949-2024),* $P_{s,f,t}$ is the proportion of fossil fuel type f (coal, natural gas, petroleum products) in sector s's total fossil fuel consumption in year t. For example, if a sector used 100 MJ of wood energy in a given year, and its fossil fuel mix that year consisted of 54% natural gas, 42% petroleum products, and 4% coal, then wood energy was assumed to displace emissions associated with 52 MJ of natural gas, 42 MJ of petroleum products, and 4 MJ of coal. Fossil fuel mix of each sector and year are computed using equation (2), based on U.S. EIA energy consumption tables described in section 2.1.

$$P_{s,f,t} = \frac{F_{s,f,t}}{\sum_{f} F_{s,f,t}} \quad \text{Eq. 2}$$

where, $F_{s,f,t}$ denotes fossil fuel consumption of fuel type f in sector s and year t.

2.3.2. Displacement factors (DF) estimation

For each fossil fuel type f, the displacement factor (DF_f) quantifies reduction in fossil CO_2e emissions achieved when wood displaces 1 MJ of energy generated from fossil fuel. Fossil fuel specific displacement factors are derived using equation (3), following ISO 13391-3 guidance [26].

$$DF_f = \frac{GHG_{nwf} - GHG_w}{C_w - C_{nw}} \quad \text{Eq. 3}$$

where, GHG_{nw} is cradle-to-gate GHG emissions of non-wood fossil fuel f (kg CO_2e/MJ), GHG_w is cradle-to-gate GHG emissions of wood energy (kg CO_2e/MJ), C_{nw} is biogenic carbon in non-wood fuels, which is considered '0' in fossil fuels. C_w is biogenic carbon content of wood per MJ, expressed as CO_2. The biogenic carbon content of wood fuel was assumed to be 50% of dry weight wood biomass and was converted to CO_2 per MJ by multiplying the carbon content with 3.67[1] [16]. The C_w in wood fuels per MJ of generated energy is estimated to be 0.130 kg CO_2/MJ heat[2] and 0.234 kg CO_2/MJ electricity.[3]

The DF_f is unitless because it is calculated from ratios of GHG emission intensities (Kg CO_2e/MJ) and carbon content in wood fuel combusted to generate 1 MJ of energy (Kg CO_2e/MJ) which share identical units and therefore cancel. A positive DF_f indicates the magnitude of GHG emission reduction resulting from using one MJ of energy generated from wood relative to one MJ of energy from fossil fuel type f. For example, a DF of 0.78 for coal, indicates that using wood to produce 1 MJ of heat avoids approximately 0.78 kg CO_2e that would otherwise be emitted from coal combustion for the same energy output.

The DF_f values for each fuel type were estimated using the most recent cradle-to-gate emissions data available in USLCI and DATASMART database [23]. These values were applied uniformly across all years in the 1949–2024 analysis period. This assumption was deemed appropriate for long term national scale analysis as the technological processes underlying the production, extraction, and delivery of fossil fuels and wood fuels do not exhibit large annual changes [27]. What varies annually and therefore drives changes in the estimated avoided fossil emissions, are (1) the sector-specific wood energy consumption, and (2) fossil fuel mix. These two variables determine the type and amount of fossil energy displaced each year and the associated reductions in fossil GHG emissions. To assess the robustness of results to uncertainty in displacement factors, we applied a ±15% sensitivity range to DF values, reflecting plausible long-term variability in cradle-to-gate emission intensities [27].

[1] Molecular weight ratio to convert carbon in wood to carbon dioxide (44/12).

[2] Average kg wood/MJ heat (0.071, from Table 2) multiplied with 0.5 carbon fraction in wood and 3.67 (to convert C to CO_2) = 0.130 kg CO_2e in wood/MJ heat.

[3] kg wood/MJ electricity (0.128, from Table 2) multiplied with 0.5 carbon fraction wood and 3.67 (to convert C to CO_2) = 0.234 kg CO_2e in wood/MJ electricity.

2.3.3. Annual avoided emissions (AE)

Annual avoided fossil fuel emissions (kg CO_2e) resulting from wood energy use for each sector in a given year were estimated by multiplying the quantity of displaced fossil energy (DQ) with the estimated DF by fossil type according to Eq (4).

$$AE_{s,t} = \sum_{f} DQ_{s,f,t} \times DF_f \quad \text{Eq. 4}$$

Where, $AE_{s,t}$ is avoided fossil emission (kg CO_2e) in a given sector *s* in a given year *t, resulting from summation of the terms across fuel type f.*

2.3.4. National annual and cumulative avoided emissions

National total avoided emissions (CO_2e) in a given year is obtained by aggregating estimated avoided emissions across four wood energy consuming sectors according to Eq. (5):

$$AE_{total,t} = \sum_{s} AE_{s,t} \quad \text{Eq. 5}$$

Total national aggregate avoided emissions for a given year results from summation of estimated avoided emissions across sectors. This annual total value represents the combined fossil fuel emissions avoided each year from wood energy consumption and resulting from the combined effect of changes in wood energy consumption and fossil fuel mixes over time. Lastly, cumulative avoided emissions over the period 1949-2024 are calculated using equation (6).

$$AE_{cumulative} = \sum_{1949}^{2024} AE_{total} \quad \text{Eq. 6}$$

3. Results

This section presents the estimated avoided fossil GHG emissions benefits associated with U.S. wood energy use, from 1949 to 2024. It reports estimated displacement factors, national aggregate and sector-specific avoided emissions, and trends in both wood energy consumption and fossil fuel energy mixes that shaped the estimated avoided emissions outcomes.

3.1. Estimated displacement factors of wood energy use

Table 3 presents the estimated *DF*s for the three fossil fuel types including coal, natural gas and petroleum products. For a sustainably managed woody biomass supply, a positive DF indicates that use of wood energy displaces more fossil fuel GHG emissions than it generates. This relationship is well-established in wood energy substitution studies [13]. Among the three fossil fuel types assessed, coal exhibited the highest displacement potential (*DF* = 0.78 for heat; and 1.26 for electricity), followed by petroleum products (0.65 for heat and 0.97 for electricity), and natural gas (0.55 for heat and 0.80 for electricity). These *DF* values reflect relatively higher cradle-to-gate emission intensities of fossil fuels, compared to wood fuels. Such relative ranking of fossil fuels, based on cradle-to-gate emission intensities (i.e., coal > petroleum > natural gas), is consistent with other bioenergy LCA studies that show largest avoided emissions when wood fuel substitutes coal, and lower benefits when substituting natural gas [13,28].

A *DF* of 0.78 for coal indicates that using wood to produce 1 MJ of heat avoids approximately 0.78 kg CO_2e that would otherwise have emitted from coal combustion to produce the same amount of heat. Conversely, natural gas exhibited lower displacement benefit, consistent with its comparatively lower cradle-to-gate emission factor [29]. The estimated *DF*s aligns with the ranges reported in prior LCA literature [13,30]. These *DF*s were applied to estimate the national aggregate and sector-specific avoided fossil emissions from wood energy use in the United States for past 76 years, results of which are described in the following section.

Table 3
Estimated displacement factors (*DF*) for three fossil fuel types in wood consuming sectors in the United States.

Primary use	Residential	Commercial	Industrial	Electric power
	Heat	**Heat**	**Heat**	**Electricity**
Coal	0.78	0.78	0.78	1.26
Natural gas	0.55	0.55	0.55	0.80
Petroleum products	0.65	0.65	0.65	0.97

3.2. Estimated avoided emissions from wood energy use

Estimated annual avoided emissions associated with the wood energy use in the U. S. averaged 178 million tonnes (t) of CO_2e, ranging from 111 to 243 million t CO_2e, (Fig. 3 and Table 4). Cumulative avoided emissions over the 76 years totaled 13,545 million t CO_2e (Fig. 4 and Table 4).

For illustration, for the latest year (2024), the industrial sector consumed 1.29E+12 MJ of wood energy, and its fossil fuel mix for that year was 4% coal, 48% natural gas, 38% petroleum. Applying the proportional displacement approach, this wood energy use corresponds to 5.16E+10 MJ of displaced coal, 6.19E+11 MJ of displaced natural gas, and 4.90E+11 MJ of displaced petroleum products. Using the DFs from Table 3 (0.78, 0.55, and 0.65 for coal, natural gas, and petroleum products respectively), the resulting avoided emissions are 5.62 million t CO_2e from coal displacement, 49.01 million t CO_2e from natural gas displacement and 45.45 million t CO_2e from petroleum products displacements, totaling 100.11 million t CO_2e of avoided emissions in the industrial sector in 2024, which matches the value reported in Table S2. This illustration demonstrates how wood energy consumption, sector specific fossil fuel mix proportions, and DFs interact to estimate annual avoided emissions. A worked example illustrating the calculation steps is provided in the Supporting Information (ES1).

Throughout most of the 76-year period, the industrial sector generated the largest avoided-emissions totals, except in the earliest decades when residential wood energy use dominated (discussed in the following section). Over the assessment period, annual avoided emissions from industrial wood energy use ranged from 44 to 146 million t CO_2e per year, averaging 105 million t CO_2e, and a cumulative total of 8000 million t CO_2e, highlighting the sector's central role in national-level fossil-fuel displacement through wood energy use.

Wood energy use in the residential sector resulted in the second-largest cumulative avoided emissions between 1949 and 2024 (3580 million t CO_2e, Fig. 4 and Table 4), although it was the dominant contributor during the early decades (Fig. 3). Although wood energy played no meaningful role in electricity generation until the 1990s, avoided emissions from wood energy use in this sector began to increase gradually after that year (Fig. 3). The commercial sector, although consistently accounting for the smallest share of avoided emissions, exhibited steady growth over time, specifically in recent decades (Figs. 3 and 4).

Because avoided emissions from wood energy use depend on both the quantity of wood energy consumed and the carbon intensity of the fossil fuels displaced each year, understanding historical patterns in sector-specific fossil fuel mixes and wood energy use is essential for interpreting the displacement benefits presented in the preceding results. These historical patterns, and the factors that shaped them, are discussed in the next section, beginning with the wood-energy consumption trends followed by sector-specific fossil fuel consumption trends.

3.3. Wood energy consumption trends

Total U.S. renewable energy consumption increased more than fourfold (1.87 to 8.58 quads) between 1949 and 2024 [4]. In contrast, wood energy consumption increased only moderately from 1.55 to 1.81

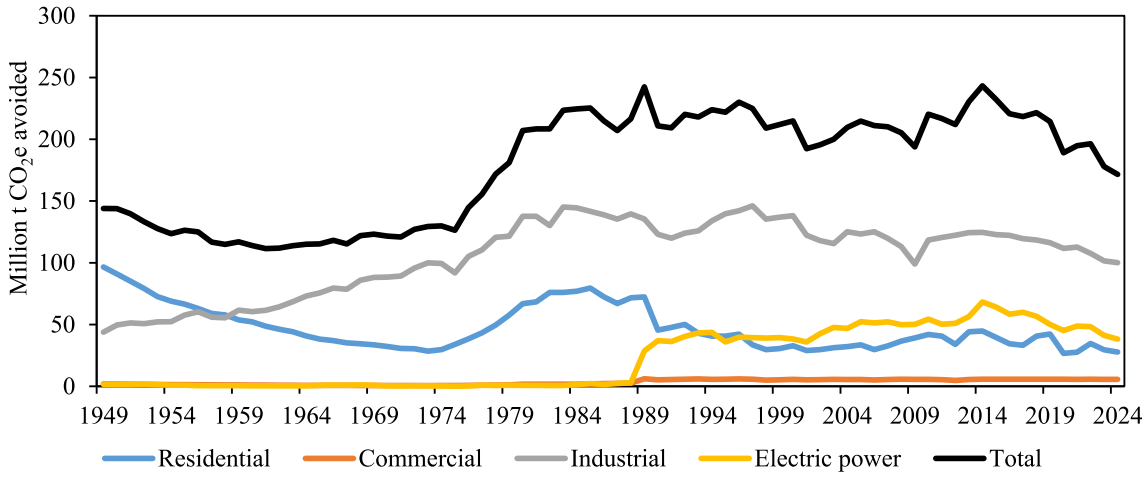


Fig. 3. Estimated annual avoided emissions from wood energy use in the United States by wood consuming sectors and combined total, 1949-2024.

Table 4
Avoided fossil GHG emissions through wood energy use across four sectors in the United States (million t CO_2e), 1949-2024.

	Residential	Commercial	Industrial	Electric power	Total
Cumulative	3576.67	248.80	8003.56	1716.01	13,545.04
Annual minimum	26.63	0.54	43.79	0.05	111.47
Annual maximum	96.61	6.08	146.09	68.27	243.25
Annual average	47.06	3.27	105.31	22.58	178.22

quads, resulting in a net decline in wood energy's share of total renewable energy consumption, from 81% in 1949 to about 21% in 2024 (Fig. 5, secondary axis). Annual wood energy consumption in each sector is provided in Supporting Information Table S1a-d.

Although total wood energy use patterns have changed only moderately, there has been a significant shift in the sectoral distribution of wood energy use (Figs. 6 and 7), decreasing in residential sector, while increasing in the industrial, electric power, and commercial sectors.

Residential wood energy consumption declined substantially, from 1.01 quads in 1949 to 0.36 quads in 2024 (Fig. 6), falling its share of 68% to only 20% in between these years (Fig. 7). The industrial sector has emerged as the biggest user of woody energy in the U.S. in more recent years, with its consumption growing from 0.47 quads in 1949 to 1.22 quads in 2024 (Fig. 6), with its increasing share from 30% to 67% (Fig. 7). Commercial wood energy use showed more gradual increase from 0.020 to 0.072 quads (Fig. 6), with its share rising from 1.5% to 4% (Fig. 7). Although the commercial sector has been a relatively small contributor to total U.S. wood energy consumption, its share has grown steadily over the years. Wood energy consumption in the electric power sector has expanded from negligible levels to 0.162 quads in 2024 (Figs. 6 and 7).

3.4. Fossil energy consumption trends

The fossil fuel consumption pattern in the U.S. shows a system-wide decline in coal use and a strong rise in natural gas consumption, while petroleum products play a transitional role that peaks mid-century and declines thereafter (Fig. 8). Data on annual fossil fuel mix of each sector is provided in Supporting Information Table S1a-d.

In the residential sector, coal use declined sharply from its early prominence in the mid-20th century to effectively zero after the mid-2000s, while natural gas became the dominant fuel, rising from less

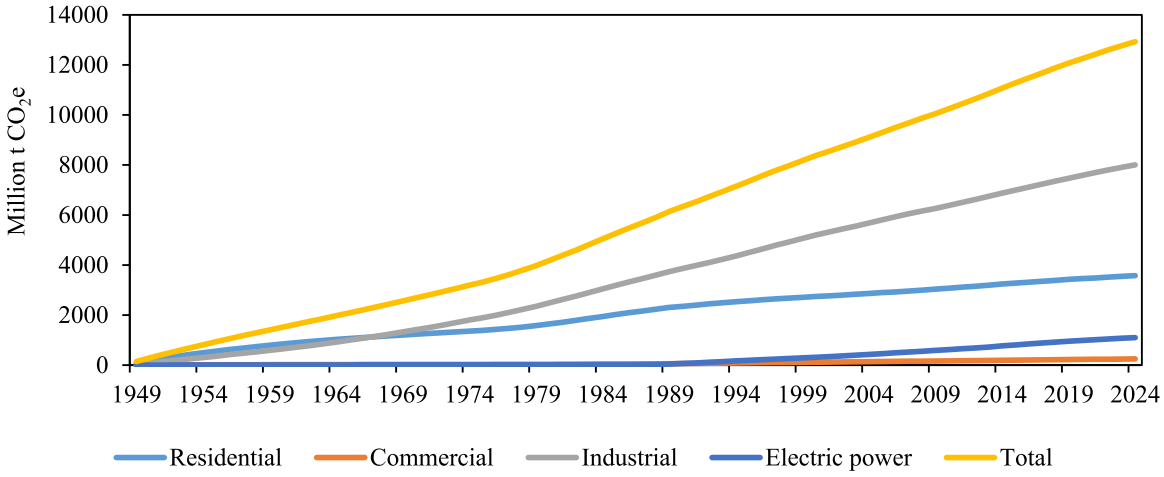


Fig. 4. Estimated cumulative avoided emissions from wood energy use in the United States by wood consuming sectors and combined total, 1949-2024.

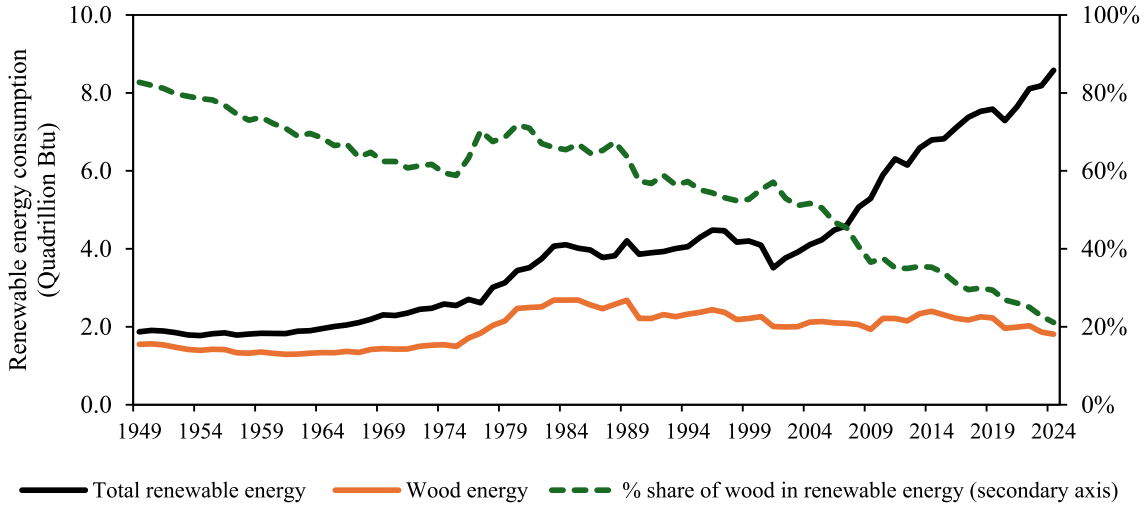


Fig. 5. Annual trends in U.S. total renewable energy consumption, wood energy consumption, and the share of wood energy within total renewable energy, 1949-2024 [4].

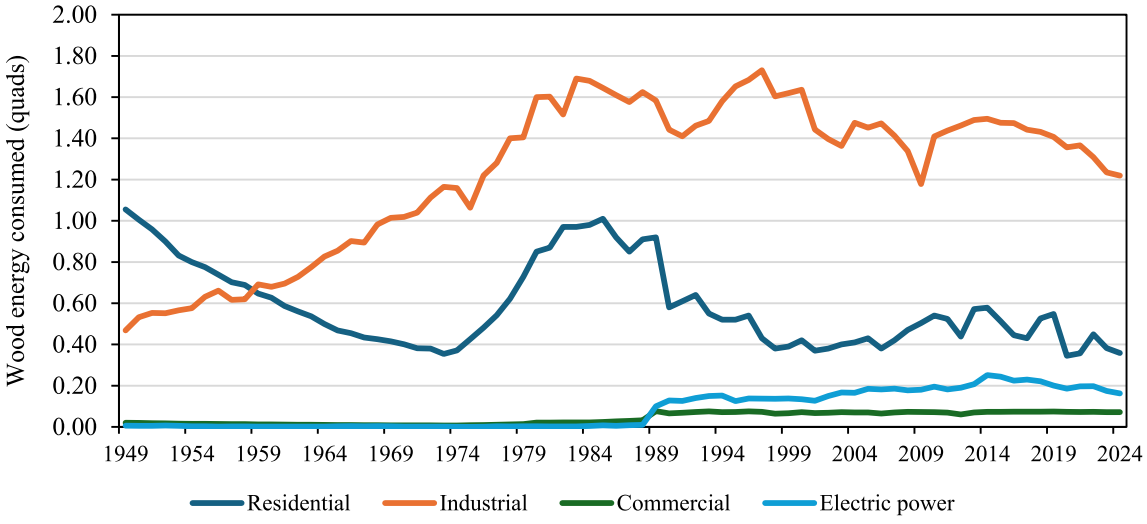


Fig. 6. Wood energy consumption in U.S. residential, commercial, industrial, and electric power sectors, 1949–2024 [4].

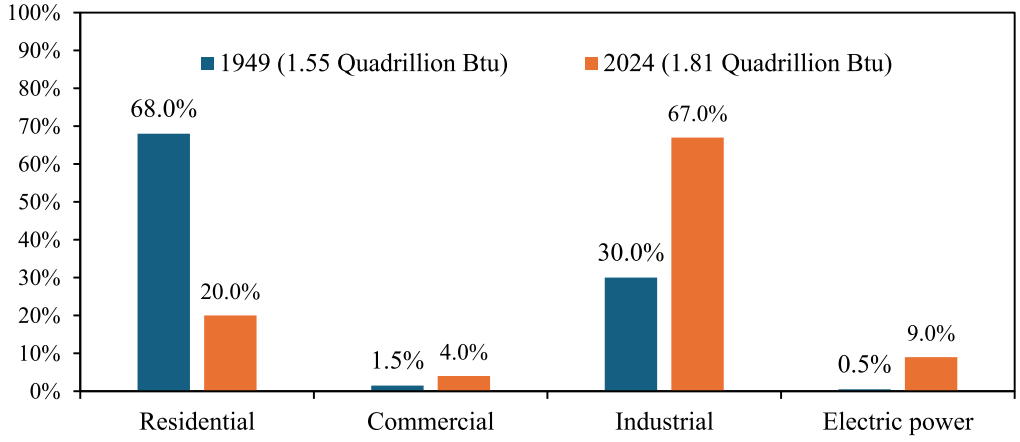


Fig. 7. Percentage share of U.S. wood energy consumption by sector in 1949 and 2024 [4].

than half of residential fossil-fuel use in 1949 to more than 80% in recent decades.

The industrial sector shows a more diverse transition. Coal's share dropped steadily from about 45% of industrial fossil-fuel use in 1949 to single-digit values today—while natural gas and petroleum products alternated as the primary fuels during different decades. A similar pattern is evident in the commercial sector, where coal use nearly disappeared by the late 1970s. Natural gas expanded rapidly and now constitutes the majority of the sector's fossil-fuel use, while petroleum products remained important but exhibit a shrinking share. The electric-power sector demonstrates the most dramatic shift. Coal dominated electricity generation for much of the 20th century, consistently representing 50–70% of fossil-fuel use. Natural gas increased modestly through the mid-century but surged after the early 2000s, eventually surpassing coal as the sector's primary fuel. Petroleum products remained a minor share throughout.

4. Discussion

The reproducible and transparent framework using LCA-based approach provides a consistent method for estimating fossil fuel displacement and avoided GHG emissions from U.S. wood energy use. The framework and avoided emission estimations are directly relevant for U.S. Forest Service sustainability reporting under Montréal Process Criterion 5, Indicator 5.24, which intends to evaluate the current and potential role of forest management efforts in offsetting fossil fuel carbon emissions. The indicator 5.24 explicitly requires reporting both the quantity of forest biomass energy produced, and the fossil fuel emissions avoided through biomass energy substitution. Historically, U.S. reporting has included only the quantity [9], omitting the avoided emissions component due to the absence of a standardized methodology. By quantifying avoided emissions over 76 years, this study fills a key national level reporting gap and offers the empirical foundation needed to complement the U.S. forest sustainability reporting obligations under the Montréal Process. It is noteworthy to mention that these estimates represent gross fossil fuel displacement benefits consistent with life cycle perspective recommended in the Montréal Process Framework. By design, they do not represent net climate mitigation effects because biogenic carbon dynamics and alternative biomass use were outside the study scope.

The results of this study demonstrate that avoided fossil-fuel GHG emissions from U.S. wood-energy use have been shaped by the interaction of two fundamental drivers: (1) the quantity of wood energy consumed in each sector and year, and (2) the carbon intensity of the fossil fuels displaced. These two factors jointly govern the magnitude, distribution, and variability of displacement benefits observed over the 76-year assessment period and explain sector specific differences in total estimated GHG reductions. Early in the time series, wood energy in the residential sector displaced predominantly coal, which was the most carbon-intensive fossil fuel in the U.S. energy mix, producing larger avoided emissions even though wood-energy quantities declined in subsequent decades. In contrast, the long-term rise in industrial wood energy use, combined with the gradual shift away from coal toward natural gas and petroleum products, resulted in continued increasing avoided emissions in the industrial sector, which ultimately emerged as the largest contributor to cumulative national displacement benefits.

The historical changes in fossil fuel consumption across sectors help explain the displacement patterns in the results. Coal use decline steadily in the residential, commercial, and industrial sectors, and later fell rapidly in electric power sector, which lowered the emission intensities of the U.S. energy system [4]. During the same period, natural gas concurrently expanded and eventually became the dominant fuel in

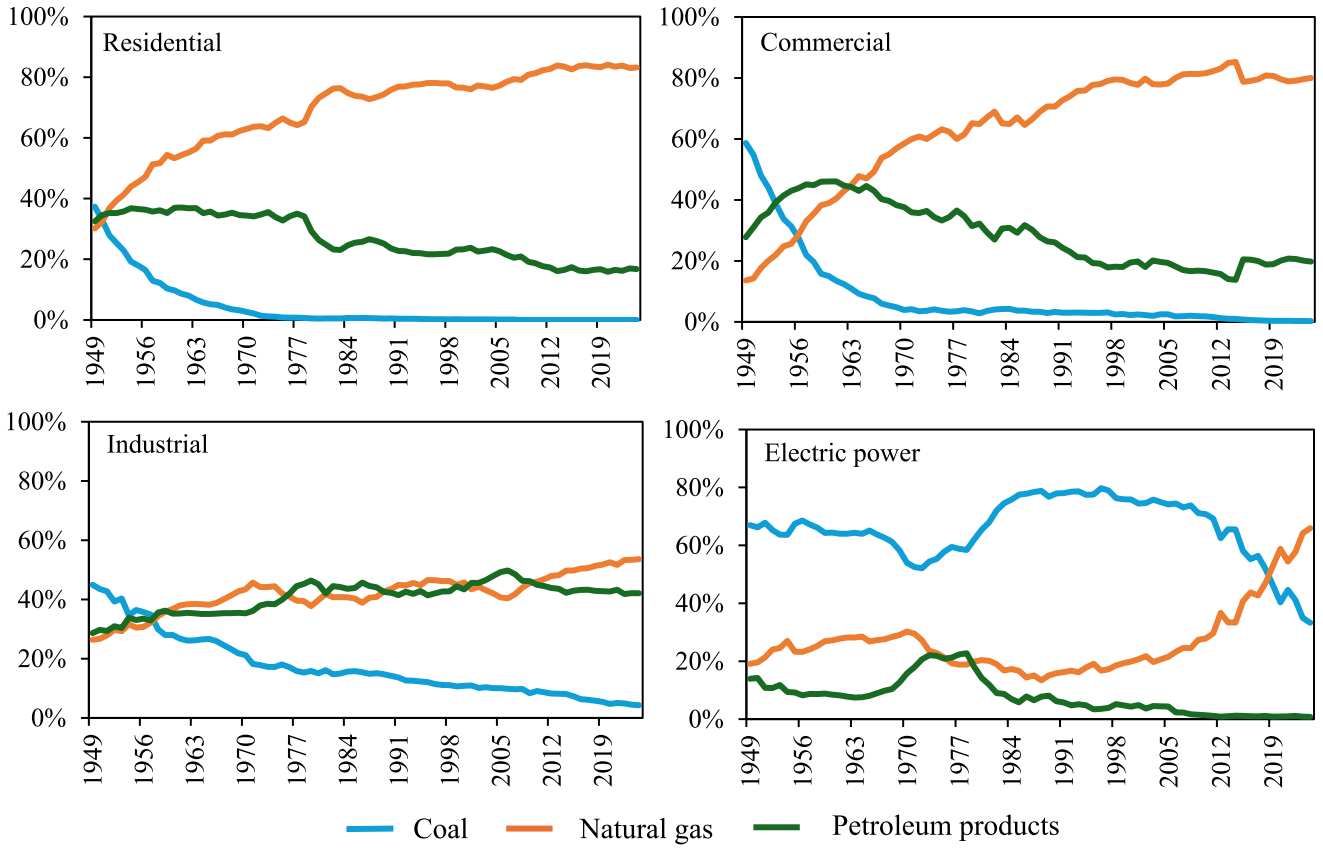


Fig. 8. Composition of fossil fuel mix consumed in the United States, 1949-2024 (Source, U.S. EPA 2025b).

residential, commercial, and industrial energy use [4,31,32]. Petroleum products were widely used in mid-century but declined as heating systems modernized and policies encouraged a shift to cleaner fuels [4,32]. These fossil fuel transitions directly shaped how much fossil fuel emissions wood energy could displace each year. For example, as coal shares diminished and natural gas took precedence, the carbon-intensity gap per unit energy between wood fuels and the fossil fuels narrowed, reducing per unit avoided emissions even when wood energy quantities remained stable or increased. This explains why residential displacement benefits declined despite initial dominance and why industrial displacement benefits remained high. Industrial systems relied more heavily on carbon-intensive fuels well into the late 20th century, allowing wood energy to continue displacing higher emitting fossil energy sources.

Historical wood energy consumption patterns also reveal structural and policy-based drivers. Residential use declined from 68% of total U.S. wood energy in 1949 to 20% by 2024 due to urbanization, widespread availability of more efficient and convenient energy sources (natural gas, electricity, heating oil), and air-quality regulations that limited residential wood burning [8,33,34]. Industrial wood-energy use increased as sawmills, paper mills, and engineered wood manufacturing facilities expanded and adopted biomass as a low-cost, on-site heat and power source, supported by both operational efficiencies and policy incentives [35,36]. Commercial and institutional uses increased gradually as biomass heating systems were deployed in schools, hospitals, and municipal buildings, especially in colder climates where biomass reduced heating costs and supported renewable-energy targets [37,38]. Although the commercial sector has been a relatively small contributor to total U.S. wood energy consumption, its share has grown steadily and is likely to continue expanding as long as the economic and operational advantages remain.

Wood-energy use in electric power sector has become more prominent in recent years than in previous decades, driven by Renewable Portfolio Standards that qualify woody biomass as a renewable resource and by co-firing strategies enabling utilities to reduce coal use [39–41]. This growth has been largely attributed to the policy efforts that continue to promote renewable energy portfolios across U.S. [41]. Woody biomass has been recognized as a qualifying renewable resource under Renewable Portfolio Standards in several states, encouraging electric utilities to incorporate it into their generation mixes [42,43]. Electric utilities have adopted both dedicated biomass power plants and co firing strategies that combine wood pellets or residues with coal to reduce emissions and meet renewable energy targets [44,45]. Together, these sectoral shifts reflect the evolving technological, economic, and regulatory landscapes influencing U.S. wood-energy adoption and associated reduction in fossil GHG emissions. These historical interpretations reflect broad sector-level patterns and should not be viewed as causal inferences, as the study does not empirically analyze drivers behind these changes.

Results of this study carry important implications for U.S. renewable-energy policy and long-term decarbonization strategies. The findings indicate that wood energy use displaced about 2.6 to 3.4% of total U.S. annual GHG emissions in years with comparable inventory data (1990-2022) shown in Supporting Information Table S3 Although these numbers may appear modest, they are environmentally and economically meaningful. For example, in 2022 alone, wood energy offsets represented 3% of total U.S. GHG emissions (6343 million t CO_2e) and 6% of fossil fuel combustion emissions within wood energy consuming sectors (2959 million t CO_2e) [19]. These figures demonstrate that wood energy provides a meaningful contribution to national decarbonization efforts and that significant unused potential remains in harvest residues that are often left on site or burned without energy recovery. Using more of these residues can displace fossil fuel emissions while also helping to reduce wildfire risks and supporting rural economy [33,46]. Industrial and electric-power sectors, two of the nation's highest emitting sectors, could benefit significantly from expanded wood energy use derived from currently underutilized forest residues [36,47]. As national renewable-energy portfolios evolve and fossil fuel price volatility persists, expanding sustainable biomass availability offers a practical, scalable pathway to further GHG mitigations [11,33,41].

Current U.S. wood energy use is dominated by byproducts from wood processing industries (e.g., sawdust, bark, and pulpwood), with limited use of forest residues. Utilizing forest residues could increase renewable energy capacity, while generating additional economic opportunities in rural and forest-dependent communities [48]. The 2023 Billion-Ton Report projects substantial growth in potential woody biomass supply including forest residues, 30.3 million dry tons by 2030 and growing to 62.7 million dry tons by 2050 [5]. For context, if this biomass were utilized in the electric-power sector to displace fossil fuels, it could avoid roughly 392 to 617 million t CO_2e. This range depends on the type of fossil fuel displaced and represents about 7% to 10% of 2022 total U.S. GHG emissions (6343 million t CO_2e). Realizing this potential depends on the capability of the U.S. energy system to utilize these forest residue resources, which are currently deemed suboptimal for pellets or direct combustion. Nevertheless, these projections illustrate that, with sufficient biomass-recovery infrastructure and market development, wood energy could play a meaningful role in national climate strategies.

5. Limitations and sources of uncertainty

Some limitations arising with methodological assumptions are listed here. A central assumption in the analysis is that wood energy displaces an equivalent amount of fossil fuels (MJ for MJ). Fossil fuel displacement is allocated according to proportional fossil fuel mix within each sector as reported in the U.S. EIA energy statistics [4]. The proportional-mix approach aligns with available U.S. EIA sectoral energy statistics, ensures transparency and reproducibility, and is widely used in national-scale substitution studies [13]. Therefore, this assumption about fuel-fuel displacement reflected the structure of energy statistics, which do not identify fossil fuel consumption mix at the facility-level. Availability of detailed, facility level or technology specific fossil fuel consumption data would allow for refined displacement factors that reflect real operational decisions rather than aggregated statistical proportions. Granular data of fuel consumption could shift DF values depending on which fossil fuel is actually displaced. However, the absence of facility-level data does not weaken the framework as the variability in DF values would only affect the magnitude and not the direction of avoided emission estimate.

Another source of uncertainty arises from assumption that DF values remain constant year-to- year. This assumption is grounded on the fact that technological processes associated with producing, extracting, and delivering both fossil fuels and wood fuels do not exhibit large annual changes. However, DFs could differ under alternative methodological assumptions (e.g., system boundary choices, different treatment of biogenic carbon), and historical technological changes could have altered emission intensities over longer timescales. These factors influence DF values by introducing variability into the underlying cradle-to-gate GHG emissions per MJ of energy for both fossil fuels and wood fuels (Eq. (3)). Prior studies indicate that a ±15% sensitivity range provides a plausibly variation in life cycle emissions intensities over time [27]. Because avoided emissions scale linearly with DF values, this ±15% sensitivity range results in proportional changes in annual and cumulative avoided emissions, while the direction and relative magnitude of fossil fuel displacement remain unchanged. Therefore, these avoided emissions estimates should be interpreted with awareness of this uncertainty.

Despite these limitations, the long-term sector level quantification presented in the study provides a robust empirical basis for interpreting historical and future carbon mitigation contributions of wood energy within sustainably managed U.S. forest systems. By offering a comprehensive national-scale estimates using a transparent, reproducible methodology, this work fills an important gap in Indicator 5.24

reporting and reinforce continued relevance of wood energy in U.S. decarbonization goals.

6. Conclusions

This study provides the first long-term, sector-specific assessment of potentially avoided fossil fuel GHG emissions from wood energy use in the United States over a 76-year period (1949–2024). By integrating LCA-derived displacement factors, historical wood energy consumption, and sector-specific fossil fuel mixes, the analysis provides an assessment framework for quantifying fossil fuel displacement. The results indicate that U.S. wood energy use avoided approximately 111 to 243 million t CO_2e annually, representing about 2.6 to 3.4% of total U.S. GHG emissions between 1990 and 2022. These results affirm that wood energy has consistently served as a renewable, lower-carbon substitute for fossil fuels and has played a vital role in national carbon mitigation efforts.

The sectoral trends in wood energy consumption showed a substantial transition from historical dominance in the residence sector toward industrial, commercial, and electric power sectors. These shifts reflect broader structural changes in energy markets, technological improvements, and evolving renewable energy policies, illustrating how wood-energy quantity, fossil-fuel mix composition, technological evolution, and policy environments have jointly shaped carbon mitigation role of U.S. wood energy. The industrial and residential sectors contributed the largest share of avoided emissions over the long term, while contributions from the commercial and electric power sectors grew steadily in more recent decades. These trends highlight sectors where expanded use of woody biomass could further support U.S. energy system decarbonization efforts. Strengthening biomass recovery infrastructure, improving residue utilization, and aligning policy incentives with sustainable forest management will be key to further expanding wood energy use and the associated fossil fuel displacement benefits.

The study provides a standardized, LCA-based framework for quantifying fossil fuel displacement and corresponding avoided GHG emissions from U.S. wood energy use, addressing a key gap in national forest sustainability reporting. These estimates can support more complete Montréal Process reporting and inform policy and forest sector decisions regarding the climate benefits of wood energy.

CRediT authorship contribution statement

Poonam Khatri: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Prakash Nepal:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Raju Pokharel:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2026.110200.

Data availability

Data will be made available on request.

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