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RESEARCH

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Environmental and economic accounting for biomass energy in Ethiopia

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Abstract

Background: Energy consumption is inextricably linked with the economy and the environment. The interlinkages are particularly important in low-income countries such as Ethiopia where biomass fuels account for more than 85% of the total energy consumed. This paper aims to assess the energy and economic values, and environmental emissions of solid biomass fuels in Ethiopia.

Methods: The study considered four common solid biomass fuels (firewood, charcoal, crop residues, and cattle dung) in Ethiopia. The amount of biomass fuels during the Ethiopian fiscal year 2015/2016 was compiled from various data sources. Prices, net calorific values, and emission factors per mass of fuels were then used to calculate the economic, energy, and emission values of the solid biomass fuels.

Results: The study showed that, in 2015/2016, the consumption of the four solid biomass fuels contributed between 33,327 and 44,547 ktoe to the total energy consumption with an estimated economic value of 4.4–7.7% of the GDP at current market prices. The stationary combustion of the biomass fuels could result in 165–219 Mt of CO_2eq emissions, whereas the fuelwood consumption could potentially impinge on the size or quality of 730 thousand ha of forest, woodlands, and shrublands.

Conclusions: The results suggest that the country should scale-up its policy measures aimed at increasing households' access to modern energy sources and energy-efficient cooking stoves while at the same time strengthening its afforestation and reforestation activities.

Keywords: Biomass energy, Energy accounting, GHG emissions, Indoor air pollution, SDGs, Ethiopia

Background

Energy production and consumption are inextricably linked with the economy and the environment. Both the quality and quantity of energy play crucial roles in shaping the sustainable development path of a country [1]. On the one hand, the availability of energy enhances economic productivity and growth [2]. On the other hand, depending on the fuel type, energy consumption may result in detrimental effects on the quality of the environment and human health [3]. The implications of alternative energy portfolios and pathways for sustainable development are particularly important in Africa [4] where access to electricity and other modern energy sources remains limited [5].

Ethiopia is not an exception. Electricity barely accounts for 3% of its total energy supply [6, 7]. Only 44% of the households have access to basic electricity supply [8]. The annual per capita electricity consumption, 100 kWh/person in 2018, is one of the lowest in the world and Africa [7]. Ethiopia is one of the top 10 countries in Africa with the highest shares of biomass fuels in their total energy consumption [9]. In 2019, biomass fuels in Ethiopia accounted for about 86% of the total energy consumption compared to the average 51% in Africa [6].

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Fuelwood consumption is one of the major causes of unsustainable utilization of biomass resources in many parts of Ethiopia [10]. Today, at least, one-third of fuelwood comes from unsustainable extraction in forests and woodlands [11] resulting in fuelwood deficiency in many districts of the country [12, 13]. Consequently, forest degradation due to fuelwood consumption accounts for about 46% of the total GHG emissions from the forestry sector [14].

Agricultural wastes (crop residues and animal dung) help to amend and enrich soil nutrients, and thus to enhance agricultural productivity. A crop model simulation shows that incorporating crop residues could increase maize yield by 45% compared to the current inorganic fertilizer application rates in Ethiopia [15]. Likewise, a field experiment in southern Ethiopia finds that an application of animal manure will raise maize yield by 51% compared to farm plots not applying animal manure [16]. As such, removing agricultural wastes for fuel has negative implications for soil nutrients cycling and animal feed supply [17–19] with considerable impact on agricultural productivity and output [13, 20].

About 93% and 63% of the households in Ethiopia use solid biomass fuels [21] and traditional three-stone stoves [8] as their primary cooking fuels and stoves, respectively. Consequently, the concentration of indoor particulate matters (PM) in Ethiopia is by far higher than the standard values suggested by the World Health Organization [22]. For instance, a case study finds that the exposure of biomass cookstove users to $PM_{2.5}$, black carbon, and carbon monoxide to be two, four, and twenty times higher than the exposure of electric cookstove users, respectively [23]. Consequently, to date, lower respiratory infections remain as one of the top three causes of morbidity and mortality in the country [24]. In 2016, about 3 million Disability-Adjusted Life Years (DALYs) and 65,000 deaths were attributed to indoor air pollution [25]. The exposure to indoor air pollution particularly affects the health of women and children [26, 27]. The percentage of children under five with symptoms of acute lower respiratory illness (ALRI) was 7% in households using biomass fuels compared to 3.5% in households using electricity or gas fuels for cooking [21]. The effects on children may bear far-reaching consequences including loss in cognitive functions [28] if exposure occurs at critical periods of childhood development [29]. The effects on human health also have economic repercussions. For instance, in 2019, indoor air pollution accounted for more than 85% of the total US$ 3.02 billion (or 1.16% of the GDP) economic output losses due to air pollution-related morbidity and mortality [28].

The preceding discussion gives an overview of the linkages between biomass fuels and the SDGs. Biomass fuels provide affordable renewable energy, at least, for rural households (SDG 7) and can contribute to poverty reduction if combusted to generate additional income such as in hotels and restaurants (SDG 1). The excessive reliance on solid biomass fuels, however, undermines the efforts to promote sustainable agriculture (SDG 2), to sustainable management of forests (SDG 15), to mitigate climate change (SDG 13), and to ensure healthy lives (SDG 3). Figure 1 depicts the linkages between solid biomass fuels and the aforementioned SDGs.

In other words, biomass fuels represent the case where energy consumption is strongly linked with the economy (agriculture, households, services, and health) and the environment (soil nutrients, forest, air quality, and climate change). These linkages are of special interest in countries like Ethiopia where biomass is the main source of energy [7], most households depend on biomass-fueled traditional stoves [8], and smallholder agriculture is the main source of employment, food, and export earnings [30, 31]. This necessitates, among others, environmental and economic accounting for biomass energy to underpin policy responses to energy-related economic and environmental issues [32] and to the SDGs. This is where this study seeks to contribute.

The existing literature, however, focuses overwhelmingly on the consumption of biomass fuel(s) by a group of households in a specific geographic region [18, 19, 33]. Other studies which include biomass resource reports [11–13] and energy balance reports [6, 7, 34] assess biomass fuels consumption at country level but provide little or no information on the economic values and emissions. It is therefore fair to argue that the extant literature provides little macroeconomic insight that could particularly help with the accounting of biomass fuels in energy- and economy-wide models.

This study attempts to fill part of these prevailing gaps. It computes energy and economic values, emissions of greenhouse gases (GHG) and indoor air pollutants, and forest and woodland degradation that could be associated with the consumption of solid biomass fuels. By doing so, the study aims to give a comprehensive picture on biomass energy in Ethiopia which, to the best of my knowledge, is the first attempt. Broadly speaking, the study also contributes to the application of the System of Environmental-Economic Accounting for Energy [32] and to the scientific discourse on energy–economy–environment nexus in developing countries [1, 4, 9].

Methods

Data and data sources

The study considered four solid biomass fuels (firewood, charcoal, crop residues, and cattle dung) widely consumed by households (rural and urban) and services

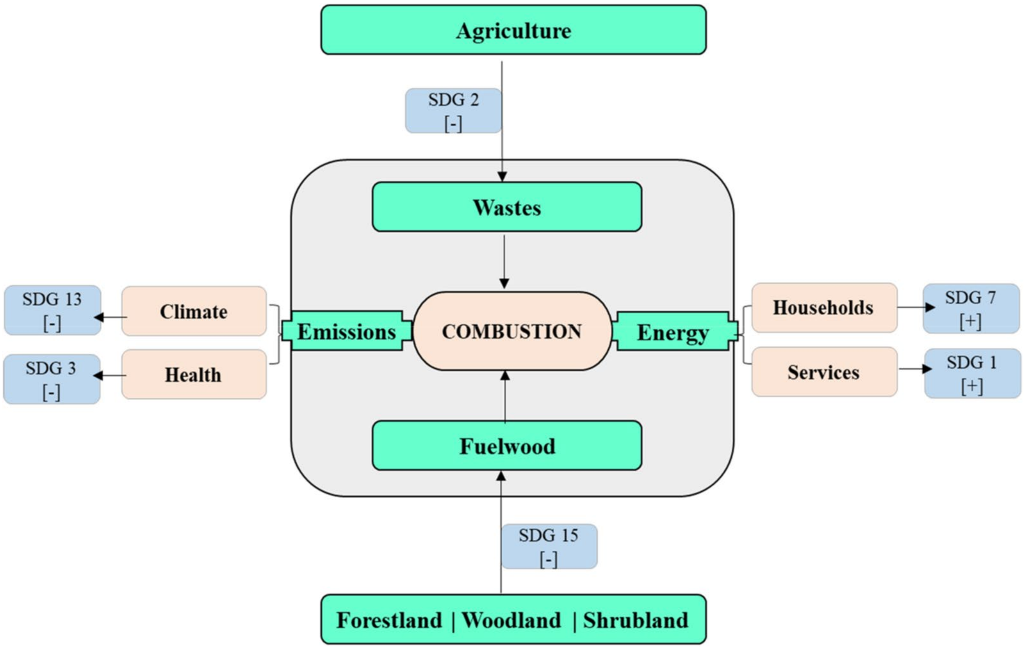

Fig. 1 The linkages between biomass fuels and the SDGs (source: author's illustration)

(commercial and public institutions) in Ethiopia. The data for biomass fuels consumption are collated from various sources [7, 12, 34]. This study constructed additional biomass fuels consumption data by combining fuelwood from [11] with newly calculated agricultural wastes from [30]. Table 1 summarizes the data and data sources for the consumption of biomass fuels. Comprehensive biomass fuels consumption data, particularly disaggregated by fuel type and user, is scarcely available which is why the consumption of biomass fuels, and the ensuing calculations in this study are built around the 2015/2016 Ethiopian fiscal year.

The environmental and economic accounting of biomass fuels requires a set of coefficients and conversion factors to estimate the energy and economic contributions as well as the effects on the environment. Table 2 summarizes the sources and uses of the main coefficients used in this study.

To obtain the actual consumption values, the potential agricultural waste (crop residue and cattle dung) resources [30] should be adjusted using relevant coefficients (crop residue-to-product ratio, dung per cattle head, and percentage of crop residues and dung allocated to fuel) which are extracted from the literature [18, 35, 36].

The actual consumption of crop residues as fuel (R) is the sum of residues from different crops (R_c) which in turn depends on the crop output (Q_c), residue-to-crop product ratio (r_c), and the portion of residues allocated for fuel (f_c) [35]:

$$R = \sum\nolimits_{c=1}^{n} R_c = \sum\nolimits_{c=1}^{n} f_c * (Q_c \cdot r_c). \tag{1}$$

The results are presented in Table 3. The total crop residue consumption obtained through this approach (19.23 million tons) is almost the same with the adjusted consumption figures from [12] despite the methodological differences.

Nevertheless, applying a slightly different and perhaps a straightforward approach, [36] estimated the annual crop residue yield (available for fuel) to be 0.9 t/ha. Multiplying the harvested area given in Table 3 (i.e., 16.5 million ha) by this yield would give us a value of approximately 14.8 million tons of crop residues available for fuel. Therefore, to allow for possible ranges of consumption, we took the average, i.e., 17 million tons as actual crop residues consumption under the COMB data source. See also Table 4.

The amount of cattle dung for fuel (CD) depends on the size of cattle population (N) and the tons of dry dung for fuel per cattle (f_d) [35, 36]:

$$\mathrm{CD} = f_d * N. \tag{2}$$

The estimated cattle population in 2015/2016 was 57.83 million [30]. The reported dung for fuel ranges from

Table 1 Description of data and data sources for biomass fuels consumption

Notation	Data type	Source	Description of data	Notes
EUEI	Biomass fuels consumption	[12]	Consumption of firewood, charcoal, residues, and dung by users (in tons) in 2013	Adjustments are made to 2015 assuming 1% annual growth rate [11]. The consumption in services sector is the difference between the total and households' consumption
MoWIE	Biomass fuels consumption	[7]	Consumption of firewood, charcoal, and agricultural wastes by users (in terajoules) in 2015/2016	The value for agricultural wastes is equally divided into crop residues and dung following the average proportion from [12, 30]. The energy values (in terajoules) are converted to mass units (in tons) for easier calculation of the economic values
AFREC	Biomass fuels consumption	[34]	Consumption of firewood, charcoal, and agricultural wastes by users (in tons) in 2015	The value for agricultural wastes is equally divided between crop residues and dung using the average proportion from [12, 30]
COMB	Biomass fuels consumption	[11]	The consumption of firewood (in cubic meters) and charcoal (in tons) in 2013	The firewood consumption in 2013 (= 110.644 million m^3) is adjusted to the year 2015 assuming 1% annual growth rate [11]. The value is converted to tons using the rate of 0.6 t/m^3 [10]. Two percent of the total firewood consumption is allocated to services based on shares from [7, 12, 34]. Charcoal use in industries is taken as charcoal use in services
COMB	Biomass fuels consumption	[30]	Estimated harvested area and output per crop (as potential resource for residues) and cattle population (as potential resource for dung) by smallholder farmers in 2015/2016	The potential supply for agricultural wastes is calculated based on crop production and cattle population [30] which is later adjusted using relevant coefficients from the literature (e.g., [13, 18, 35–37]) to arrive at the actual consumption

The notations are acronyms from the data sources: *EUEI* European Union Energy Initiative [12], *MoWIE* Ministry of Water, Irrigation, and Electricity [7], *AFREC* African Energy Commission [34], and *COMB* "combined" fuelwood data from the Ministry of Environment, Forest, and Climate Change [11] with calculated agricultural wastes data from the Central Statistical Agency [30]

Table 2 Description of data and data sources for main coefficients

Data type	Source	Description of data	Uses
Coefficients	[13, 18, 35–40]	Residue-to-crop product ratio, the fraction of crop residues available for fuel, and dry dung for fuel per cattle	To calculate consumption of crop residues and cattle dung as fuel
Coefficients	[41]	Energy contents (net calorific values) per ton of the fuels	To derive the energy values
Coefficients	[42–44]	Prices per ton of the fuels	To compute the economic values
Coefficients	[41, 45]	Emissions of gases per ton of the fuels	To estimate emissions of gases due to biomass fuels combustion
Coefficients	[46]	Above-ground biomass stock (tons of wood) per hectare of forest and woodland	To calculate the potential effects of fuelwood consumption on the size and quality of forest and woodlands

Table 3 Estimated crop residues for fuel in Ethiopia, 2015/2016

Crops	Crop area ('000 ha)	Crop output ('000 t)	Residue-to-product ratio	Portion available for fuel	Residues as fuel ('000 t)
Teff	2978	4577	2.4	0.01	110
Barley	1135	2055	1.3	0.03	77
Wheat	1742	4293	1.3	0.03	161
Maize	2959	8213	1.9	0.35	5318
Sorghum	1916	4355	1.9	0.35	2820
Pulses	2089	3171	2.0	0.01	63
Oilseeds	895	810	2.0	0.75	1214
Vegetables	265	1251	0.3	0.75	281
Roots	491	7215	0.3	0.75	1623
Fruits	92	680	0.4	0.75	178
Chat	251	203	1.5	0.75	228
Coffee	654	415	1.5	0.75	466
Sugarcane	30	1377	0.3	0.75	310
Enset	442	5310	1.5	0.75	5974
Other crops	571	1155	1.0	0.35	404
Total	16,509	45,078			19,229

Crop-specific area and production are from [30]. The residue-to-crop product ratios are averages whenever ranges are available [13, 35–40]. The proportion of the residues allocated to fuel are primarily based on [18]

Table 4 Biomass fuels consumption in Ethiopia, 2015/2016 (million tons, Mt)

Source	User	Firewood	Charcoal	Residues	Dung	Total
EUEI	Households	74.64	5.53	19.26	22.01	121.44
	Services	3.47	0.17	0.00	0.00	3.64
	Total	78.11	5.69	19.27	22.01	125.08
MoWIE	Households	67.05	1.48	12.70	12.70	93.93
	Services	0.66	0.03	–	–	0.69
	Total	67.71	1.51	12.70	12.70	94.62
AFREC	Households	77.65	4.95	10.00	10.00	102.59
	Services	0.72	–	–	–	0.72
	Total	78.37	4.95	10.00	10.00	103.31
COMB	Households	66.35	0.65	17.04	14.84	98.88
	Services	1.35	0.05	–	–	1.40
	Total	67.71	0.70	17.04	14.84	100.29

The "–" denotes data are not reported by the source approximately 0.2 to 0.3 t/cattle [35–37, 47]. The procedure gives us an average cattle dung consumption of approximately 14.84 million tons.

Table 4 presents the amount of biomass fuels consumed by households and services for the year 2015/2016. The consumption data vary across data sources which may be due to the scope and methods employed in the respective reports. We purposely kept these ranges of values to capture the possible ranges of biomass energy consumption, and its economic value and emissions.

Table 4 shows that the annual consumption of solid biomass fuels ranges from 95 Mt [7] to 125 Mt [12]. Households consume about 99% of the total biomass fuels. The average annual biomass fuel consumption is about 106 Mt. The consumption of charcoal ranges from 0.7 [11] to 5.7 Mt [12]. Firewood accounts for 62–76% of the total biomass fuels consumed. Only [12] indicates that the services sector uses agricultural wastes although we note that the volume and the share are negligible. One can also see that the new consumption data (i.e., COMB source) lay between the estimates reported by other data sources.

Energy, economic, and environmental accounting

Energy values

Energy derived from the combustion of a specific fuel, f, depends on both the mass of the combusted fuel (M_f) and the net calorific values (or energy content) per unit mass of that fuel (c_f). The total biomass energy consumed (EN) is then obtained by aggregating energy produced from the combustion of the four biomass fuels:

$$EN = \sum_{f=1}^{4} c_f \cdot M_f. \tag{3}$$

Economic values

The aggregate economic value (EC) is computed as the sum of the products of the mass of the combusted fuel (M_f) and the unit price of the fuel (p_f):

$$EC = \sum_{f=1}^{4} p_f \cdot M_f. \tag{4}$$

The prices used are the average retail prices of 3 years. It should be acknowledged that retail prices are influenced by urban markets which include trade and transport margins compared to the prices that might be received in rural areas where the majority of biomass fuel consumption occurs. We used those reported retail prices as basic prices are hardly available for biomass fuels.

Emissions of air pollutants

The combustion of biomass fuels emits pollutants which have implications to climate change and human health. We applied the default fuel specific emission factors for each greenhouse gas (CO_2—carbon dioxide, CH_4—methane, and nitrous oxide—N_2O) from the *stationary* combustion of fuels in the residential and commercial or institutional settings [41, 48].[1] The emission factors (average of stove types, when available) for health-damaging indoor air pollutants (CO—carbon monoxide and PM—particulate matters) are extracted from [45] which provides average emission factors for household stoves for laboratory or simulated kitchen measurements using the Water Boiling Test (WBT). The total emission of a specific pollutant (EM) is then calculated as the sum of the products of emission factor (e_f) and the combusted fuel mass (M_f):

$$EM = \sum_{f=1}^{4} e_f \cdot M_f. \tag{5}$$

Table 5 presents the summary of values and sources of the coefficients used in Eqs. 3, 4, and 5.

Effects on forest, woodlands, and shrublands

Fuelwood consumption impinges on the area (i.e., deforestation) or quality (i.e., degradation) of forests, woodlands and shrublands. Dividing the amount of fuelwood consumed by the above-ground biomass stock per hectare of forestland could indicate the size of deforestation or degradation (FD) due to fuelwood. The fuelwood refers to both firewood (FW) and charcoal equivalent of wood (CW). The latter is the product of mass of charcoal (MC) and the carbonization ratio (cr = tons of wood to a ton of charcoal). The carbonization ratio is influenced by various factors and hence the value varies, for example, from 4.35 to 12.6 tons of wood for a ton of charcoal in Africa [50]. Based on information from [11, 12], we calculated and applied the ratio of 5 tons of wood to a ton of charcoal in Ethiopia. The above-ground biomass stock per hectare of forestland (bs = 122 t/ha) is obtained from [46][2]:

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[1] It should be noted here that emissions of CO_2 from biomass fuels are usually estimated and reported under the Agriculture, Forestry and Other Land Use (AFOLU) sector, not under the Energy sector [48]. Accordingly, CO_2 emissions from combustion of biomass fuels for energy are reported as only information items with the energy sector to avoid double counting [48], whereas the non-CO_2 emissions from biomass fuels are reported with the energy sector. This, however, does not matter in this study as its objective is to estimate emissions from the combustion of biomass fuels (not from net removal of biomass) while how to record and report emissions in the national emissions inventory is beyond the scope of this study.

[2] We use this conversion factor value (i.e., above-ground biomass stock per ha) for being the latest submitted by Ethiopia's National Forest Inventory [46]. It is, however, high compared to conversion factors reported in other studies such as, for example, 44 t/ha and 60 t/ha [33], and 75 t/ha [34] which may attribute to the continuous re-classifications of forests and changes in data sources [46].

Table 5 Summary of key coefficients and conversion factors

Parameter	Unit	Firewood	Charcoal	Residues	Dung	References
Economic						
Price	US$/t	24.52	326.7	12.26	76.46	[42–44]
Energy content	MJ/kg	15.60	29.50	11.60	11.60	[41]
Emission factor						
CO_2	kg/t	1747	3304	1160	1160	[41]
CH_4	kg/t	4.68	5.90	3.48	3.48	[41]
N_2O	kg/t	0.06	0.03	0.05	0.05	[41]
CO_2eq	kg/t	1883	3460	1261	1261	[41]
CO	kg/t	41.90	180.40	101.20	33.80	[45]
PM	kg/t	2.45	1.95	7.10	2.93	[45]

The price for crop residues is assumed to be 50% of firewood as in [49]. CH_4 and N_2O emissions are converted into carbon dioxide equivalent (CO_2eq) using their global warming potentials of 25 and 298, respectively

MJ megajoules, *t* tons, *kg* kilograms

Table 6 Energy from biomass fuels in Ethiopia, 2015/2016 (kilo tonne of oil equivalent, ktoe)

Source	User	Firewood	Charcoal	Residues	Dung	Total
EUEI	Households	27,806	3893	5338	6099	43,135
	Services	1293	119	0	0	1412
	Total	29,099	4012	5338	6099	44,547
MoWIE	Households	24,977	1045	3519	3519	33,059
	Services	247	21	–	–	269
	Total	25,224	1066	3519	3519	33,327
AFREC	Households	28,925	3484	2771	2771	37,950
	Services	270	–	–	–	270
	Total	29,195	3484	2771	2771	38,220
COMB	Households	24,718	461	4721	4111	34,011
	Services	504	34	0	0	539
	Total	25,223	495	4721	4111	34,550

$$\mathrm{FD} = \frac{\mathrm{FW} + \mathrm{CW}}{bs} = \frac{\mathrm{FW} + (cr * \mathrm{MC})}{bs}. \tag{6}$$

In the "Results" section, for the sake of comparison, degradation that could be attributed to fuelwood with and without accounting for charcoal equivalent of wood are presented. It is important to note here that the results obtained through Eq. 6 represents the maximum potential effects on the quantity or quality (or both) of forest, woodlands, and shrublands. If one assumes all fuelwood consumption involves unsustainable clearing of standing natural (or plantation) forests, the degradation could amount to deforestation. If additional information is available, one may also focus on the effects only due to the unsustainable extraction by multiplying this potential effect by a portion of fuelwood consumption that comes from unsustainable extraction.

Results

Energy values

Table 6 presents the energy values obtained from biomass fuels which range from 33,327 to 44,547 ktoe. The energy based on [12] represents the highest value. The difference is primarily explained by the quantity of agricultural wastes reported by this source compared to others (see also Table 4). The energy 38,220 ktoe [34] represents the second highest total biomass energy.

The energy values obtained from the biomass fuel consumption data constructed by this study (34,550 ktoe) are comparable with estimates reported elsewhere. For instance, biomass energy is reported to be 33,257 ktoe in 2015 and 35,747 ktoe in 2018 [6] while the country's energy balance reported biomass energy values of 31,699 ktoe (in 2013/2014), 33,327 ktoe (in 2015/2016), and 34,890 ktoe (in 2017/2018) [7].

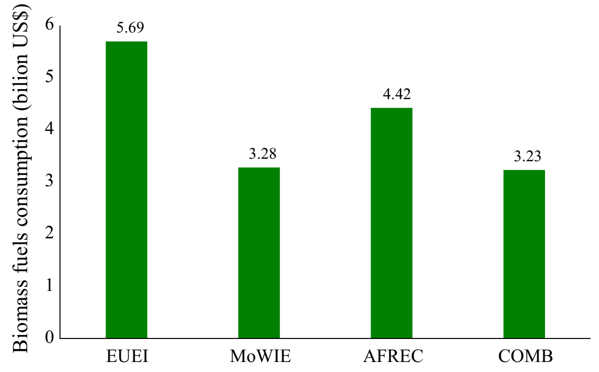

Fig. 2 Economic values of biomass fuels in Ethiopia, 2015/2016 (billion US$)

Economic values

The consumption of biomass fuels in 2015/2016 valued from US$ 3.2 to 5.7 billion (or 4.4–7.7% of the national GDP at current market prices). See also Fig. 2. Firewood followed by cattle dung makes up the largest economic contribution. The volume of consumption (Table 4) explains the economic role of dung fuel relative to charcoal even though the latter has the highest unit price (Table 5). The average ratio of fuelwood (firewood and charcoal) and agricultural waste fuels (crop residues and dung) to the GDP at current market prices is 3.8% and 1.8%, respectively.

The economic values calculated here are generally comparable with a range of available estimates. For instance, for fuelwood alone, the value is reported to be US$ 1.8 billion at 2013 prices [11] which of course is lower than the value calculated in this study (US$ 2.2–3.8 billion). The differences can be explained by the upward adjustments to the consumption quantities in this study, and the lower prices used in [11]. Despite this, however, the ratios of fuelwood to GDP in this study and [11] are around 4%. We also applied the share of cattle dung fuel and fuelwood in the gross value-added of livestock (6.8%) and forestry (85%) activities in 2010/2011 [47] to their corresponding gross value-added figures in 2015/2016 [31]. The procedure gives us a value of approximately US$ 2.5 billion in 2015/2016 compared to US$ 3.0–5.5 billion estimated in this study. The difference is partly explained by the prices and the methods of estimation. Firstly, this study used retail prices compared to basic prices applied in [47]. Secondly, the economic value of fuelwood is arguably underestimated in the national income accounts [47] due to the incomplete accounting of households' subsistence fuel use [51]. Applying a better accounting method, [51] finds the economic value of fuelwood to be around US$ 5.9 billion (or 4.52% of the GDP) in 2012/2013 which is even bigger than the highest value for fuelwood (US$ 3.8 billion) calculated in this study.

Table 7 Emissions from stationary combustion of biomass fuels in Ethiopia, 2015/2016 (million tons, Mt)

Source	GHG	CO	PM
EUEI	218.84	6.99	0.4
MoWIE	164.76	4.82	0.30
AFREC	189.90	5.53	0.30
COMB	170.12	5.19	0.33

Emissions

The average calculated emissions of CO and PM pollutants are 5.63 and 0.33 Mt whereas the GHG emissions range approximately from 165 to 219 Mt CO_2eq. It is worth mentioning a couple of caveats regarding the emissions calculated and reported in this study. First, the GHG emissions are based on the stationary combustion of the fuels unlike the common approach pursued in the national GHG emission inventory, i.e., based on the net removal of woody biomass stock [48]. Second, the emission factors used in the calculations are default values. In practice, however, emission factors are influenced by several factors such as by the location and frequency of burning, compactness and moisture content of the fuel, flow dilution, the type and age of the stove, and other factors [52, 53]. As such, the total emissions presented in Table 7 should be taken as indicative only.

Previous estimates on GHG emissions exclusively from the *stationary* combustion of solid biomass fuels are scarcely available. Biomass fuels are embedded within the Land Use Change and Forestry (LUCF) sector in the country's Nationally Determined Contribution (NDC) [54]. The Ethiopian NDC estimated 125 Mt CO_2eq emissions from the LUCF sector in 2020 [54] which is by far lower than the emissions presented in Table 7. The differences could be attributed to two main reasons. The first is related to the differences in the methodological approaches employed. As already mentioned earlier, the emissions in this study are computed based on the *stationary* combustion of fuels not based on the *net removal* of woody biomass stock.[3] Besides, fuelwood removed from trees in settlements and the non-CO_2 gases from biomass fuels combustion are accounted for in the energy sector not in the LUCF sector [48]. The energy sector in

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[3] Further discussion on the differences can be found in volumes 2 and 4 in [48]. Accordingly, reporting is generally organized "according to the sector actually generating emissions or removals. There are some exceptions to this practice, such as CO_2 emissions from biomass combustion for energy, which are reported in AFOLU Sector as part of net changes in carbon stocks" [48].

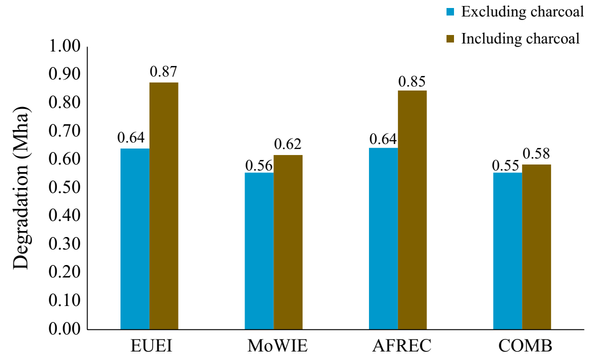

Fig. 3 Forest, woodland, and shrubland area potentially impinged by fuelwood collection in Ethiopia, 2015/2016 (million ha, Mha)

Ethiopia's NDC refers to the electric power sector [14] which is virtually all from renewable sources [31] and thus estimated to emit only 11 Mt CO_2eq in 2020 [54]. The second is related to the differences in the quantities of biomass fuel consumption. The background document for the NDC states that "the total amount of woody biomass degradation is projected to increase from around 14 million tonnes in 2010 to 23 million tonnes in 2030" [14].[4] These figures are, however, by far lower than the annual fuelwood consumption figures reported in several previous studies (e.g., [10–12, 34, 51]). It is most likely that the NDC background document [14] is referring to the net annual woody biomass removals although it is not explicitly stated. It also seems that the emissions from the combustion of crop residues and animal dung fuels are unaccounted for since it was assumed that 75% of the residues are reintroduced into the soil [14] in contrast to the evidence indicating that about 85% of the crop residues are removed for fuel and animal feed [17–19, 36].

Effects on forests, woodlands, and shrublands

If we assume that the whole fuelwood (including charcoal) consumption involves unsustainable extraction, as depicted in Fig. 3, annual degradation caused by fuelwood collection could amount from 0.58 to 0.87 million ha. If we rather focus only on a third of the fuelwood consumption, a fraction reported to involve unsustainable extraction [11], the average forest degradation would scale down to 243 thousand of ha. The calculated and reported figures here are much bigger than the total annual deforestation rate of 73 thousand ha [46], whereas they make sense if we compare with the loss of forest, woodlands and shrublands which amounted from 14.1 to 16.2 million ha (i.e., from 1.1 to 1.25 million ha/year) between 2000 and 2013 [11].[5] As such, given several other causes of deforestation, the values presented in Fig. 3 should be considered as potential effects (not specifically deforestation) of fuelwood collection on forests, woodlands, and shrublands. The loss could be in terms of size (loss in forest, woodland, and shrubland area), quality (degradation of their capacity to provide ecosystem services) or both.

Put alternatively, the calculated results show that fuelwood collection in Ethiopia largely involves degrading woodlands and shrublands, collecting deadwood, and cutting branches, leaves, and twigs rather than directly cutting and clearing standing forest trees. Available evidence corroborates the argument. For instance, of the total annual supply of wood fuel in 2013, only 25% comes from natural woody biomass [12]. The rest is collected from on-farm (household) trees (56%), deadwood (12%), and branches, leaves and twigs (6%). This also makes sense when we consider the fact that about 90% of the firewood is consumed by rural households [12].

Discussion

The study results demonstrated the excessive reliance on biomass fuels affects the quality of the environment in several ways with implications to climate change, agricultural productivity, and human health. Significantly reducing the share of biomass energy is therefore one of the crucial steps to transform the country's energy system while at the same time reducing forest degradation, fulfilling its ambitious climate change mitigation targets, dampening the competition between agriculture and energy for agricultural wastes, and reducing indoor air pollution-related burden of diseases.

This requires, among others, to strengthen and accelerate policy measures that increase households' access to modern sources of energy and cooking stoves. Since barely 5% of the households use electricity for cooking, the deployment of off-grid solar technologies can provide an immediate solution for significant number of unelectrified rural households [8]. Equally important is expanding improved cooking stoves (ICS) as only 18% of the households use manufactured stoves [8]. Even biomass-fueled ICS can reduce the consumption of biomass fuels by up to 31% and their $PM_{2.5}$ emissions by 50–58% compared to the traditional cooking stoves [22]. Deploying and effectively using about 10 million ICS could reduce the consumption of biomass fuels by 25–30% and their annual GHG emissions by 18–22% in Ethiopia [55]. It also needs to increase the access to alternative household

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[4] The NDC [54] made revisions on the original GHG emission estimates in the Climate-Resilient Green Economy (CRGE) strategy [14].

[5] Forest cover and deforestation rates for Ethiopia vary significantly across sources due to the lack of up-to-date reliable forest area estimates [10].

cooking fuels and stoves. Ethanol cooking stoves could help to exploit the substantial but underutilized molasses from sugar factories while providing cleaner household energy, saving households' fuel expenditure, and reducing emissions and deforestation [56]. Domestic biogas digesters, on the other hand, can help to convert animal dung into fuel (clean energy for rural households) and bio-slurry (fertilizer for crop cultivation) [49]. The large-scale deployment of efficient biomass stoves as well as other clean fuel stoves, however, are surrounded with several technical, institutional, and financial constraints [49, 56] while electricity to productive uses may get priority over households' cooking [12]. It is therefore necessary to parallelly scale-up afforestation, reforestation, and agroforestry activities to ensure that the annual fuelwood harvest stays well below the sustainable woody biomass yields [11] while at the same time increasing carbon sequestration in forests and woodlands [14].

That being said, the study results should be interpreted with caution. The unit prices are average national retail prices unadjusted to rural areas, where the bulk of biomass fuels is consumed, although the economic values in this study (both in absolute terms and relative to GDP at current market prices) are comparable to the previous estimates. It should of course be noted here that estimating the economic value of fuelwood as well as other forest products in Ethiopia is non-trivial task as the bulk of forest products are non-marketed as they are freely collected and consumed within rural areas [11, 51]. The emission factors are default values from global studies, and the GHG emissions (which are based on stationary combustion of fuels) are by far bigger than the previous estimates. Future research that applies country and fuel (and if possible, stove) specific emission factors and accounting the health effects will be helpful.

Conclusions

This paper estimated the energy, economic values, GHG emissions, and degradation of forests associated with the combustion of solid biomass fuels in Ethiopia. It showed that biomass fuels are important sources of energy, but also causes of emissions of air pollutants and degradation of forest, wood, and shrublands.

The study results imply that energy transition is critically needed in the country not only for its indispensable role to realize the country's economic transformation goals, but also for its spillover effects on the environment and human health. Given households consume approximately 99% of the total biomass fuels, policy measures are needed to improve rural households' access to cleaner energy sources (e.g., electricity, biogas, ethanol) and energy-efficient cooking stoves. It should also be recognized that biomass energy is a cross-sectoral issue that requires working across ministries of energy, environment, agriculture, health, and innovation and technology.

Notwithstanding its limitations, the study attempted to link biomass energy with the economy, environment, and the SDGs. It provided results that can easily be integrated with future studies that aimed at accounting and modeling the country's overall energy system.

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Author contributions
AWY conceptualized, wrote, and reviewed the manuscript. The author has read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The author declares that he has no competing interests.

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