Energy Nexus 3 (2021) 100017

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

Economic contributions and synergies of biogas with the SDGs in Ethiopia

Amsalu Woldie Yalew[a,b,c]

[a] Ca' Foscari University of Venice, Via Torino 155, Venice 30172, Italy
[b] Euro-Mediterranean Center on Climate Change, Via della Libertà 12, Venice 30175, Italy
[c] RFF-CMCC European Institute on Economics and the Environment, Via della Libertà 12, Venice 30175, Italy

ARTICLE INFO

Keywords:
Domestic biogas
Rural energy
Energy transition
SDGs
Ethiopia

ABSTRACT

Domestic biogas technology helps to foster sustainable development in different ways. It is particularly important in countries like Ethiopia where about 80% of the population lives in rural areas, and more than 90% of the households use solid biomass for cooking. In light of this, the Government of Ethiopia has launched a National Biogas Programme in 2008. The Programme, now in its third phase, has successfully installed tens of thousands of biogas digesters. This paper aims to give a macroeconomic insight on the role of the biogas sector in Ethiopia. The annual gross value of biogas outputs reached USD 7.7 million in 2015/16. Installing biogas digesters contributes USD 1.4 million each year to the construction industry. Results of the study indicate that the micro and macroeconomic contributions of biogas sector partly rely on the effective utilization of its co-product (i.e., the slurry) as fertilizer. Agricultural policies of the country should therefore highlight and link domestic biogas production with the extension services.

Introduction

Households' energy consumption accounts for nearly 90% of the overall energy consumption in Ethiopia [28] where 93% of the households use solid biomass fuels (firewood, charcoal, branches, leaves, twigs, dung, and crop residues) for cooking [9]. The Ethiopian energy mix therefore entails negative externalities on the environment (e.g., deforestation, soil nutrient loss) and health (e.g., due to indoor air pollution). One third of the fuelwood comes from the unsustainable extraction of forests and woodlands [26]. Consequently, fuelwood consumption is the single largest driver of greenhouse gas (GHG) emissions in the land use change and forestry (LUCF) sector [14]. Indoor air pollution is responsible for about 5% of the total disease burdens [33]. Removing and burning agricultural wastes for energy, on the other hand, compromises soil fertility [30] that could reduce agricultural GDP by 7% [40].

As such, diversifying and shifting to cleaner energy sources has recently become one of the key energy sector strategies in Ethiopia [14]. Biogas serves as one of the potential clean energy fuels to foster rural energy transition in the country [4,23] since 80% of the population lives in rural areas depending on smallholder agriculture [1,29]. Of the estimated 17.8 million smallholder peasants in 2015/16, about 15.8 million farmers raise one or more livestock species from which about 8 million farmers own three or more cattle heads [1]. Therefore, technically speaking, between 1.1 and 3.5 million households in Ethiopia could install domestic biogas digesters [20,23]. This represents huge resource (and demand) potential to advance the biogas sector in Ethiopia. As a result, in 2008, the Government of Ethiopia launched a National Biogas Programme of Ethiopia (NBPE) [12]. Chiefly supported by SNV, The Netherlands Development Organization, the NBPE was able to install tens of thousands of digesters in the past decade. However, although it is highly subsidized, the adoption and use of domestic biogas technology remains below expectations [4]. For instance, until December 2019, only 26,867 digesters (of the 66,000 planned) were installed [10].

The existing literature on biogas in Ethiopia is scant and largely discusses at households' level. It mainly focuses on the financial feasibility of domestic biogas technology [17,34], on the determinants of its adoption [4,24], on its environmental benefits [25], on the resource potentials [12,23], and on the institutional barriers affecting the sector [5,20]. Several conclusions can be drawn from the existing literature. First, biogas digesters are financially feasible only with the availability of subsidies [5,12]. Second, the level of income and education, the size of cattle holding, access to credit, and distance to the main fuelwood source strongly influences the adoption of biogas technology among rural households [4,24]. Third, biogas digesters have the potential to reduce GHG emissions [12,25], and indoor air pollution [5]. Fourth, some of the installed digesters were not functioning properly due to shortages of water and dung supplies, installation, and maintenance problems, and in some cases loss of interest and abandonment [5,20,23]. Fifth, the alignment between stakeholders is poor [5,20]. Put together, the biogas sector in Ethiopia is still in a niche phase in which the private sector involvement remains limited [20,36].

E-mail address: amsaluwoldie.yalew@unive.it

https://doi.org/10.1016/j.nexus.2021.100017
Received 9 September 2021; Received in revised form 29 October 2021; Accepted 1 November 2021

Table 1
Summary of key parameters and data sources.

Item	Unit	Value	Sources
National Average Prices (NP)			
Residues	ETB/kg	0.31	CSA [8]
Dung	ETB/kg	1.99	CSA [8]
Firwood	ETB/kg	0.62	CSA [8]
Charcoal	ETB/kg	8.49	CSA [8]
Kerosene	ETB/lt	12.78	CSA [8]
Adjusted Rural Prices (RP)			
Residues	ETB/kg	0.15	Adjusted from CSA [8]
Dung	ETB/kg	1.00	Adjusted from CSA [8]
Firwood	ETB/kg	0.31	Adjusted from CSA [8]
Charcoal	ETB/kg	4.25	Adjusted from CSA [8]
Kerosene	ETB/lt	12.78	Adjusted from CSA [8]
Energy Contents			
Residues	kWh/kg	4	INFORSE [18]
Dung	kWh/kg	3	INFORSE [18]
Firewood	kWh/kg	4.5	INFORSE [18]
Charcoal	kWh/kg	7	INFORSE [18]
Kerosene	kWh/lt	10	INFORSE [18]
Fuel Shares			
Residues	Percent	15–29	EREDPC [12]; EUEI [13]; Negash et al. [30]
Dung	Percent	12–51	EREDPC [12]; EUEI [13]; Negash et al. [30]; Berhe et al. [4]
Firewood	Percent	16–68	EREDPC [12]; EUEI [13]; Negash et al. [30]; Berhe et al. [4]
Charcoal	Percent	1–8	EREDPC [12]; EUEI [13]; Negash et al. [30]; Berhe et al. [4]; Teka et al. [37]
Kerosene	Percent	0.15–5	EREDPC [12]; EUEI [13]; Berhe et al. [4]; Teka et al. [37]
Substitution Ratios			
Residues	kg/m^3	7.06	EREDPC [12]
Dung	kg/m^3	9.15	EREDPC [12]; Gwavuya et al. [17]
Firwood	kg/m^3	6.34	EREDPC [12]; Gwavuya et al. [17]
Charcoal	kg/m^3	1.82	EREDPC [12]; Gwavuya et al. [17]
Kerosene	lt/m^3	0.61	EREDPC [12]
Biogas Prices			
Biogas based on NP	ETB/m^3	8	Calculated
Biogas based on RP	ETB/m^3	4	Calculated
Slurry based on fertilizer (DAP) price	ETB/kg	0.92	Calculated
Macroeconomic Variables			
Gross Domestic Product (GDP)	Million ETB	1568,098	NBE [29]
Exchange Rate	ETB/USD	21.1	NBE [29]

Note: 1 ETB ≈ 0.05 USD, and 1 m^3 =1000 liters. The prices of crop residues (as fuels) are assumed to be 50% of the prices for firewood [12].

That being said, to the best of my knowledge, research on the macroeconomic aspects of the biogas sector in Ethiopia is lacking. Neither the country's energy statistics [28] nor the national income accounts [27] report the values of the biogas sector. As a result, the biogas sector has received little or no attention in both scientific and policy discourses pertaining to energy system modeling and transformation in the country.

This paper attempts to fill this gap. It identifies and depicts the backward and forward linkages of the sector and the ways through which the sector supports the achievement of the Sustainable Development Goals (SDGs). More specifically, this paper estimates the macroeconomic benefits and costs of the sector. The paper aims to stimulate future research on energy system modeling and transformation to explicitly account for biogas fuel. It also seeks to inform energy sector planners in agrarian countries like Ethiopia regarding the co-benefits of diversifying, decentralizing, and shifting into cleaner rural energy sources.

The remainder of the paper is organized as follows. Section 2 briefly presents the linkages of biogas sector with other economic activities and the SDGs. Section 3 presents the materials and methods. Section 4 presents the results which is followed by the discussion and conclusions in Sections 5 and 6.

Table 1

The nexus between biogas and the SDGs

Domestic biogas digesters produce biogas fuel and slurry. Biogas fuel is one of the clean household energy fuels that can be used for both cooking and lighting [5]. In a way, biogas improves households' disposable income as it converts animal waste to wealth. The slurry enriches soil nutrients thereby improving agricultural productivity. The installation of biogas digesters, on the other hand, contributes to the construction industry, and adds on the rural infrastructure base. Since most of the rural households cannot cover the upfront investment costs, the installation of digesters generates additional demand for microfinance loans [5,12].

Given the country's cattle stock, rural population, and reliance on solid biomass fuels, if proper institutional and policy supports are laid out, the Ethiopian biogas sector has the potential to evolve as an industry by itself [20,36]. It is therefore important to highlight the linkages of biogas production with other economic activities and the SDGs.

The domestic biogas sector links rural energy with crop agriculture (forward linkage), and with the livestock, construction, and microfinance sectors (backward linkages). These backward and forward linkages also represent the channels through which the biogas sector contributes to achieving the SDGs. Fig. 1 summarizes these linkages with other economic sectors (livestock, crop cultivation, energy, construction, government, and financial intermediaries) and the SDGs (1, 2, 3, 5, 7, 9, 13 and 15).

The expansion of the biogas sector has the potential to particularly help to achieve the SDG 7 (affordable and clean energy), SDG 3 (ensure healthy lives and promote wellbeing), SDG 2 (end hunger and promote sustainable agriculture), and SDG 13 (climate action) [19,39].

The schematic presentation of the backward and forward linkages of biogas sector (such as the one given in Fig. 1) helps to visualize the multiple effects of the growth in the biogas sector and to design a bet-

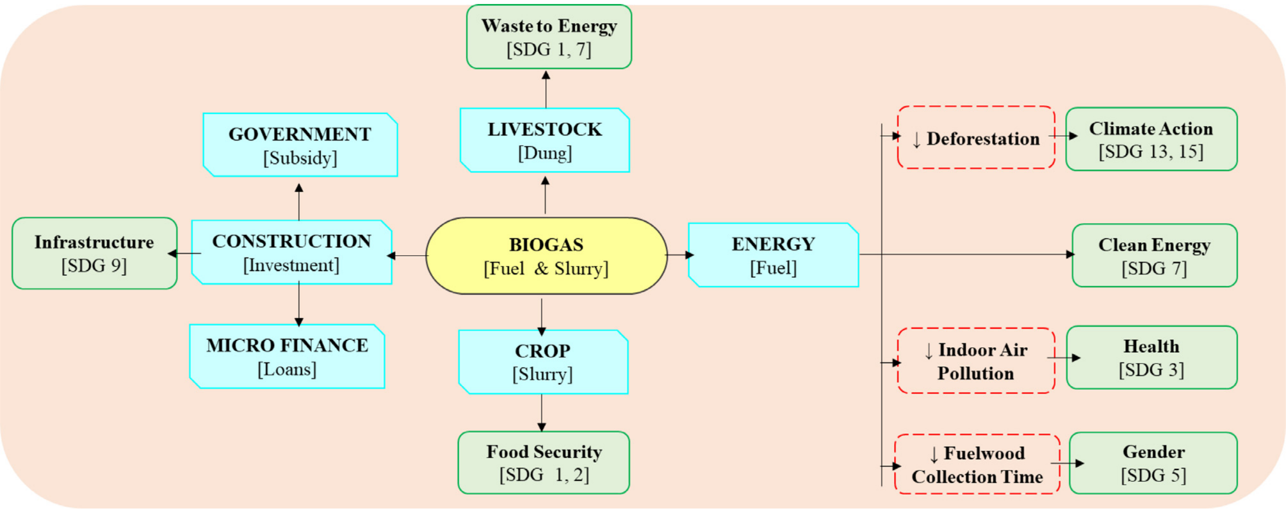

Fig. 1. The linkages between domestic biogas production, economic activities, and the SDGs
Source: Author's illustration.

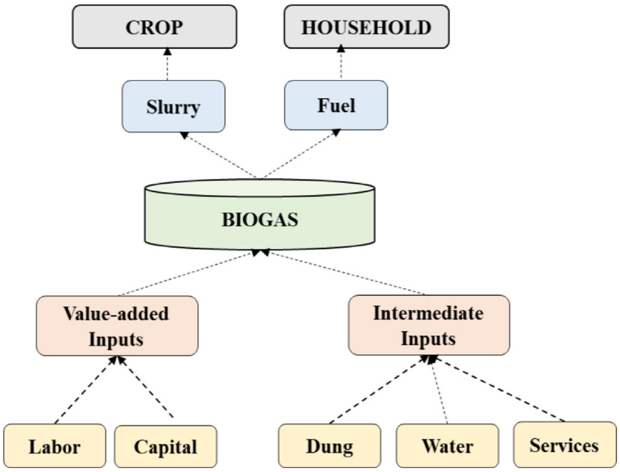

Fig. 2. A production technology nest for domestic biogas production
Source: Author's illustration.

ter coordination mechanism among stakeholders. It is also the starting point to stipulate a production technology nest to represent biogas production process, as a separate economic activity, within multisectoral energy-economy models to assess the energy, economic, environmental, and health benefits of biogas. For example, one can consider the production technology nest in Fig. 2 to capture the biogas production process in multisectoral economic models such as in computable general equilibrium models (see also, [7]).

Fig. 2 depicts how different intermediate inputs (dung, water, and maintenance services), and primary factors of production (labor and capital) are aggregated in the biogas production process that yields biogas fuel (consumed by households) and slurry (used in crop growing activities).

Materials and methods

The overall approach

There exists little or no market transaction for domestic biogas products (fuel and slurry) and their inputs of production (dung, water, unpaid family labor) in developing countries like Ethiopia. This makes estimating the economic contribution of the biogas sector difficult. The common approach is therefore to elicit based on the values of replaced commodities, i.e., other cooking fuels (for the biogas fuel) and fertilizer (for the slurry). However, oftentimes, neither most of the substitutable fuels (e.g., dung, crop residues, firewood) nor organic fertilizers are traded in rural areas. In such cases, it is common to use shadow prices (see, for example, [17]) or market prices of related commodities (which is followed in this study) to impute the prices of the inputs, substitutable fuels, and organic fertilizer.

Due to data availability, all estimated values in this study are built around 2015/16 Ethiopian fiscal year and, where it is necessary, converted from Ethiopian Birr (ETB) to US Dollar (USD) using the average exchange rate of the year, i.e., 21.1 ETB/USD [29]. The national average prices are obtained from Central Statistical Agency of Ethiopia [8]. Because such prices are usually influenced by urban markets, to give a range of values, the study rather applies two sets of prices for the substituted fuels (firewood, charcoal, dung cake, and crop residues) to estimate the unit value of biogas fuel. These are the national average prices (NP), and the adjusted rural prices (RP = 50% of NP). The inputs (fresh dung, water, and family labor) are valued using the set of adjusted rural prices (RP) as they are entirely collected from rural areas. Such adjustment to rural prices is also common in the country's national income accounting practice [27].

It is natural to expect lower prices for commodities produced and sold in rural areas on two main grounds. First, unlike those in urban areas, rural prices hardly include the transport and trade margins. Second, oftentimes, economic activities in rural areas use cheap (or unpaid) family labor, and communal natural resources (e.g., river streams, woodlands) implying lower production costs compared with the corresponding activities and products in urban areas.

Unit values of outputs

Calculating the unit value of biogas fuel requires information on the number, types, and prices of fuels that are likely to be substituted, their substitution ratios (units of a substituted fuel to a unit of biogas, i.e., the calorific value or energy content of the presumably substituted fuel relative to that of biogas), and household energy mix (the share of a substituted fuel in the household energy consumption) [12]. We presume that households exhibit "fuel stacking" behavior and thus use multiple fuels to meet their energy demand [4]. In other words, households may substitute several fuels by biogas at the same time.

The NBPE assumes biogas can replace crop residues, dung cake, firewood, charcoal, and kerosene [12]. We took this bundle of fuels to be the benchmark case. Besides, we assume that households may use and hence substitute different fuel mixes reported in other four case studies [4,13,30,37]. The fuel shares are computed after deriving the gross calorific values of the fuels [18]. When available, the average substitution ratio is taken [12,17]). Otherwise, we stick to the substitution ratios given in the NBPE [12]. It is important to note here that substitution ratios are influenced the burning efficiencies of the fuels in addition to their respective calorific values [17,18].

All in all, we were able to construct five different cases of rural household energy mixtures each representing a different combination of fuel numbers, shares, and substitution ratios to finally compute average unit prices of biogas fuel for each set of prices. The unit value of biogas fuel is then computed as following:

$$P_b = \sum_{f=1}^{n} P_f \cdot S_f \cdot R_f \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \qquad (1)$$

Where, P_b = unit price of biogas fuel, P_f = unit price of substitutable fuel *f*, S_f = share of substitutable fuel *f* in the total reported household energy (varies across case studies), R_f = substitution ratio or units of replaceable fuel *f* to a unit of biogas fuel, and *f* = substitutable fuels (slightly varies across case studies).

The unit value of the slurry, on the other hand, is estimated based on its soil nutrient content relative to inorganic fertilizer. In general, about 80% of the total solids fed into a digester can be expected to come out [34] with no loss in the form or quantity of the nutrients [17,34]. Accordingly, the price of slurry is computed as following:

$$P_s = \frac{P_i}{D_i} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \qquad (2)$$

Where, P_s = unit price of slurry, P_i = unit price of the replaceable inorganic fertilizer, and D_i = quantity of dung equivalent to a unit of the inorganic fertilizer. On average, 16 kg of dried dung is equivalent to 1 kg of diammonium phosphate (DAP) fertilizer [17,34]. The price of DAP is 14.76 ETB/kg (Legesse et al., 2019).

The overall procedure gives us rounded up prices of 4 ETB/m^3 of biogas fuel (valued at adjusted rural prices), and 8 ETB/m^3 of biogas fuel (valued at national average prices), and 0.92 ETB/kg of slurry.

Production costs

Biogas production (BG) requires animal dung (D), water (W), labor (L), capital (K), and repair and maintenance services (M) as summarized below:

$$BG = f(D,\ W,\ L, K,\ M) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \qquad (3)$$

The technical coefficients (input-output ratios) for many of the inputs are obtained from the NBPE [12] and unpublished reports from the SNV-Ethiopia [35,36]. The estimated prices for fresh dung and water are 0.40 ETB/kg and 0.002 ETB/liter, respectively. The imputed price of fresh dung is also very close to the price of fresh dung (0.37 ETB/kg) derived based on the soil nutrient content of dung using the approach employed in Gwavuya et al. [17]. The costs of water estimated here are however lower than the costs reported in Gwavuya et al. [17] which were computed based on opportunity costs of 30 min of labor needed to collect water per day. This study instead explicitly accounted labor cost (discussed below) to easily map and fit the biogas production process within multisectoral energy-economy models (see also Fig. 2). It makes sense to separately account the costs of water, despite negligible, as evidence shows many digesters have stopped functioning due to water shortages [5,20,23].

Collecting, mixing, and feeding inputs to the biogas digester as well as removing and distributing slurry require daily labor services. We assumed an average digester needs a service of 30 min/day (182.5 h/year) of unskilled laborer [17].[1] Based on daily wage rates from CSA [8], we estimated the labor cost to be around 1.60 ETB/day (or 584 ETB/year) per digester. Capital costs are obtained by dividing the total investment costs per digester by 20, which is estimated life years of a biogas digester [17].[2] The total investment cost of average-sized biogas plant (or 6 m^3 size) was around 16,465 ETB (780 USD) in 2016 [35] giving annual capital costs of 823 ETB (39 USD) per digester.[3] Evidence shows that many installed digesters stopped functioning, among others, due to lack of maintenance and technical supports [5,20]. It is therefore necessary to include the costs for repair and maintenance services which are assumed here to be 100 ETB/year per digester [5].

Digester (installation) costs

The installation of a fixed-dome digester, the most common digester model in Ethiopia, exhibits the same production technology nest as any construction activities. It needs cement, sand, gravel, stones, pipping and fittings, and labor [17,36]. Explicitly accounting the construction costs of digesters particularly helps to assess the economy-wide effects of implementing large-scale biogas programs.

Estimating the total investment (construction) cost requires information on, at least, the number of digesters installed each year and the investment cost per digester. Between 2009 and 2019, on average, the NBPE installed about 1791 digesters per year [10]. As already pointed above, the construction cost per average-sized biogas plant is 16,465 ETB (or 780 USD) [35]. The total construction costs of a digester are shared among costs of construction materials (36%), appliances, accessories, and fittings (23%), and labor costs (40%) if the dome is constructed by mason [36]. It also involves additional administrative costs (2%) if the dome is rather constructed by bio-digester construction enterprises (BCEs) [36].

Results

An average biogas digester (6 m^3 size) is assumed to produce 1710 liters (or 1.71 m^3) of biogas fuel per day using 45 kg of fresh dung and 45 liters of water [12]. The corresponding annual values are 624,150 liters (624.15 m^3) of fuel using 16,425 kg of fresh dung and 16,425 liters of water. An average digester therefore produces biogas fuel that values from 127 to 250 USD/year, and slurry that values 230 USD/year. Taken together, an average digester yields a total benefit of USD 357 to 480 per year. It incurs production costs of USD 383/year from which dung accounts for 81%. The remainder of the production costs are shared among capital (10%), and labor (7%), and water and maintenance services (≈ 2%).

Next, the average values per digester are multiplied by the total number of digesters installed until 2016 (16,000 according to [35]) to obtain the gross value of outputs and production costs at macro level. It should be recalled here that the number of digesters for calculating annual investment costs is rather the number of digesters installed per annum (i.e., 1791) [10]. Table 2 summarizes the aggregate values.

The estimated annual macroeconomic output from domestic biogas production ranges from USD 5.70 to 7.68 million whereas production costs are estimated around USD 6.12 million. The contribution of digester installation (29.5 million ETB/year or 1.4 million USD/year) is however negligible. The results show that not only the profit margins are small but also could be negative when the prices of displaced fuels are low justifying the need for subsidies [5,12].

Table 2 also shows that the slurry accounts for 48 to 64% of the total benefits. This corroborates previous studies which reported the share of slurry to be 40 to 88% [35], and 65% [17] of the total economic benefits.

---

[1] Also, personal communication with Mr. Melis Teka, a Senior Biogas Expert at SNV-Ethiopia, on 14 June 2021.

[2] The average life years of a digester may in fact range from 15 to 25 years or even beyond [4,17].

[3] Amortizing the investment costs over 20 years with 10 % rate of interest also gives not that much different capital costs (867 ETB/year).

Table 2
Gross value of outputs and production costs of domestic biogas in Ethiopia (2015/16, USD).

	Per digester		Total (Million)	
ITEMS	RP	NP	RP	NP
OUTPUTS				
Biogas	127	250	2.03	4.01
Slurry	230	230	3.67	3.67
Total benefits	357	480	5.70	7.68
INPUTS				
Dung	310	310	4.96	4.96
Water	1.53	1.53	0.02	0.02
Labor	27.7	27.7	0.44	0.44
Capital	39	39	0.62	0.62
Maintenance	4.74	4.74	0.08	0.08
Total production costs	383	383	6.12	6.12
INVESTMENT				
Construction costs	780.31	780.31	1.40	1.40

Notes: RP= valued at adjusted rural prices, and NP= valued at national average prices.

The implication is that the success of biogas digesters highly depends on the use or sale of slurry of as fertilizer.

The total benefits per digester in Table 2 (USD 357 to 480) are however higher than the USD 224 benefit reported in Berhe et al. [4]. This may accrue to the differences in the type and share of replaced fuels, the method used to estimate the value of slurry, and the geographic scope. The benefits of biogas in Berhe et al. [4] excludes the value of replaced dung fuel (perhaps assuming it is free disposal) despite the study reported dung as the main source of energy among its sample households. The same study also calculated the value of the slurry based on the incremental yield of *teff* crop which is largely controlled by other sets of climatic and agronomic factors.

Discussion

Overall, the results show that the total gross value of outputs and investment costs related to the biogas sector to be around USD 9 million per annum. The ratio of this sum to the national GDP is however miniscule (ca. 0.012%) revealing that the sector is currently in early development phase [20]. This should be interpreted with caution though. The cumulative number of digesters considered in this analysis is hardly 1.5% of the potential households (1.1 to 3.5 million) which could install biogas digesters [20,23].

Fully exploiting this potential will particularly underpin achieving SDG 9 which aims at “building resilient infrastructure, promoting inclusive and sustainable industrialization” [38]. It can also be aligned with Target 9.3 which involves increasing “the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets” [38].

The benefits that accrue from biogas sector go beyond fuel and slurry. Biogas also contributes to reduce deforestation and emissions (as it replaces fuelwood combustion), to improve soil fertility (as it replaces crop residues for fuel), to reduce the health impacts of indoor air pollution on women and children (as it reduces solid biomass combustion), and to reduce workload on women and children (as it reduces time needed to collect solid biomass fuels) [5,17,23]. Although eliciting the monetary values of these and other co-benefits of domestic biogas was beyond the scope of this study, their values cannot be undermined [17,25]. An average digester could, for instance, cut GHG emissions from the stationary combustion of fuelwood by 1.9 t CO_2eq per year [25], and thus could seek carbon finance [12,25].

It therefore needs to constantly raise households’ awareness regarding the multiple benefits of biogas digesters [5,23], to ensure a continuous supply of water and dung especially during drought years [20], and to avail affordable biogas stoves fitting to baking *injera* that accounts for 50 to 60% of rural households’ energy consumption [4,23].[4]

Pulling together, given its prospects of growth and environmental co-benefits, it is imperative to incorporate biogas particularly in those energy models dealing with the energy-economy-environment (E3) or water-energy-food (WEF) nexus. One of the crucial steps in this direction is to identify the backward and forward linkages of biogas production and estimate the macroeconomic contributions. This is what the present study attempted to accomplish. The study results can easily feed into future research on the economic, social, and environmental effects of biogas compared to other centralized or decentralized energy sources under the current or future economic and energy scenarios. Such research questions can be addressed using models with multiple agents such as computable general equilibrium (see, for example, [7]) and agent-based (see, for example, [41]) models.

That being said, the focus of this study was only on the existing domestic biogas technology in the country, i.e., fixed-dome digester that involves anaerobic digestion of cattle dung mixed with water [12]. It is however known that Ethiopia has sizeable but underutilized amount of biomass residues [15] that can be converted into biogas with advanced technologies. In light of this, future research is highly needed on the technical and economic viabilities of alternative biogas technologies that could process other organic wastes such as sewage sludge [2,3,16,31], crop residues [6,21,32], and other animal wastes [11,22]. Such research will, among others, help to broaden the scope of biogas technology and product markets in Ethiopia or Africa in general.

Conclusions

The shift in rural household energy mix is the crucial step towards the overall energy transition in Ethiopia. Clean and decentralized rural household energy sources such as biogas have substantial role in this regard. This study therefore attempted to provide a macroeconomic analysis of the Ethiopian domestic biogas sector. It illustrated the backward and forward linkages of the sector, and estimated the gross value of biogas products along with their production costs. It also highlighted the nexus between biogas and the SDGs. The results suggest that the economic attractiveness of the biogas sector is highly influenced by the effective utilization of slurry as fertilizer, and the types and prices of replaced fuels.

It is therefore imperative to properly recognize the backward (livestock) and forward (crop) linkages of biogas in the country’s agricultural policies and extension services. It also requires laying out concrete and coordinated institutional and policy supports to make the sector more attractive to the private sector.

The study comes with caveats. Most of the biomass fuels assumed to be replaced by biogas, and the inputs are usually non-marketed commodities in rural areas. In that sense, the economic estimates in this study might be sensitive to the imputed biomass fuel prices. This is regardless of the efforts made such as taking averages (substitution ratios, prices, and shares) whenever a range of values are available. It also makes optimistic assumptions regarding the operational rates of installed digesters and the ability of households to properly apply the slurry. The estimated values in this study should therefore be considered only as indicative meant to shed a light on the intersectoral linkages and the macroeconomic relevance of the biogas sector.

Notwithstanding its limitations, the study suggests that future research on energy transition in developing countries should not overlook the importance of biogas and hence needs to incorporate within energy planning models.

---

[4] *Injera* is a traditional tiny flat-round bread made from cereals.

Declaration of Competing Interest

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

Funding

This work has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie Grant Agreement No. 886309. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Acknowledgements

I am grateful to Mr. Melis Teka, a Senior Biogas Expert at SNV-Ethiopia, for providing relevant reports and his invaluable expert opinions.

References

[1] AgSSAgricultural Sample Survey 2015/16, Central Statistical Agency, Addis Ababa, 2016.

[2] A. Arias, C.R. Behera, G. Feijoo, G. Sin, M.T. Moreira, Unravelling the environmental and economic impacts of innovative technologies for the enhancement of biogas production and sludge management in wastewater systems, J. Environ. Manag. 270 (2020) 110965, doi:10.1016/j.jenvman.2020.110965.

[3] P. Batlle-Vilanova, L. Rovira-Alsina, S. Puig, M.D. Balaguer, P. Icaran, V.M. Monsalvo, F. Rogalla, J. Colprim, Biogas upgrading, CO_2 valorisation and economic revaluation of bioelectrochemical systems through anodic chlorine production in the framework of wastewater treatment plants, Sci. Total Environ. 690 (2019) 352–360, doi:10.1016/j.scitotenv.2019.06.361.

[4] M. Berhe, D. Doag, G. Tesfay, C. Keske, Factors influencing the adoption of biogas digesters in rural Ethiopia, Energy Sustain Soc 7 (2017) 10, doi:10.1186/s13705-017-0112-5.

[5] T.G. Berhe, R.G. Tesfahuney, G.A. Desta, L.M. Mekonnen, Biogas plant distribution for rural household sustainable energy supply in Africa, Energy Policy Res. 4 (1) (2017) 1–20, doi:10.1080/23815639.2017.1280432.

[6] C.P. Borges, J.C. Sobczak, T.R. Silberg, M. Uriona-Maldonado, C.R. Vaz, A systems modeling approach to estimate biogas potential from biomass sources in Brazil, Renew. Sustain. Energy Rev. (2021) 110518, doi:10.1016/j.rser.2020.110518.

[7] F. Bosello, L. Campagnolo, F. Eboli, R. Parrado, Energy from waste: generation potential and mitigation opportunity, Environ Econ Policy Stud 14 (2012) 403–420, doi:10.1007/s10018-012-0043-5.

[8] CSAAverage Retail Prices of Goods and Services: July/2016, Central Statistical Agency, Addis Ababa, 2016.

[9] CSA and ICFEthiopia Demographic and Health Survey 2016, Central Statistical Agency, Addis Ababa, 2017.

[10] DiBiCooBiogas Markets and Frameworks in Argentina, Ethiopia, Ghana, Indonesia, and South Africa, Digital Global Biogas Cooperation, 2020 Available at https://dibicoo.org/d3-3-biogas-markets-and-frameworks-in-argentina-ethiopia-ghana-indonesia-and-south-africa/. Accessed on May 10, 2021.

[11] S. Emadian, M. Kuzulcan, M.A. Küçüker, B. Demirel, T.T. Onay, Enzymatic pretreatment of chicken manure for improved biogas yield, in: V. Naddeo, M. Balakrishnan, Choo K.H (Eds.), Frontiers in Water-Energy-Nexus—Nature-Based Solutions, Advanced Technologies and Best Practices For Environmental Sustainability, Springer, Cham, 2020, pp. 357–358.

[12] EREDPCNational Biogas Programme of Ethiopia, Ethiopian Rural Energy Development and Promotion Centre, Addis Ababa, 2008.

[13] EUEIBiomass Energy Strategy: Ethiopia, European Union Energy Initiative, Eschborn, 2013.

[14] FDREUpdated Nationally Determined Contribution, Federal Democratic Republic of Ethiopia, Addis Ababa, 2021.

[15] E.W. Gabisa, S.H. Gheewala, Potential of bio-energy production in Ethiopia based on available biomass residues, Biomass Bioenergy 111 (2018) 77–87, doi:10.1016/j.biombioe.2018.02.009.

[16] S. Giarola, O. Forte, A. Lanzini, M. Gandiglio, M. Santarelli, A. Hawkes, Techno-economic assessment of biogas-fed solid oxide fuel cell combined heat and power system at industrial scale, Appl. Energy 211 (2018) 689–704, doi:10.1016/j.apenergy.2017.11.029.

[17] S.G. Gwavuya, S. Abele, I. Barfuss, M. Zeller, J. Müller, Household energy economics in rural Ethiopia: a cost-benefit analysis of biogas energy, Renew Energy 48 (2012) 202–209, doi:10.1016/j.renene.2012.04.042.

[18] INFORSEManual On Sustainable Energy Technologies Solutions For Poverty Reduction in South Asia, International Network for Sustainable Energy-South Asia, 2007 Available athttps://www.inforse.org/asia/ Accessed on June 20, 2021.

[19] IPE Triple Line, Demonstrating the potential of biogas to contribute to the SDGs, Shell Foundation, 2020 Available at https://shellfoundation.org/learning/demonstrating-the-potential-of-biogas-to-contribute-to-the-sdgs/. Accessed on June 20, 2021.

[20] L.M. Kamp, E.B. Forn, Ethiopia's emerging domestic biogas sector: current status, bottlenecks and drivers, Renew. Sustain Energy Rev. 60 (2016) 475–488, doi:10.1016/j.rser.2016.01.068.

[21] H. Lin, A. Borrion, W.A. da Fonseca-Zang, J.W. Zang, W.M. Leandro, L.C. Campos, Life cycle assessment of a biogas system for cassava processing in Brazil to close the loop in the water-waste-energy-food nexus, J. Clean. Prod. 299 (2021) 126861, doi:10.1016/j.jclepro.2021.126861.

[22] L. Lin, F. Xu, X. Ge, Y. Li, Improving the sustainability of organic waste management practices in the food-energy-water nexus: a comparative review of anaerobic digestion and composting, Renew. Sustain. Energy Rev. 89 (2018) 151–167, doi:10.1016/j.rser.2018.03.025.

[23] M.G. Mengistu, B. Simane, G. Eshete, T.S. Workneh, A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia, Renew. Sustain Energy Rev. 48 (2015) 306–316, doi:10.1016/j.rser.2015.04.026.

[24] M.G. Mengistu, B. Simane, G. Eshete, T.S. Workneh, Factors affecting households' decisions in biogas technology adoption, the case of Ofla and Mecha Districts, northern Ethiopia, Renew. Energy 93 (2016) 215–227, doi:10.1016/j.renene.2016.02.066.

[25] M.G. Mengistu, B. Simane, G. Eshete, T.S. Workneh, The environmental benefits of domestic biogas technology in rural Ethiopia, Biomass Bioenergy 90 (2016) 131–138, doi:10.1016/j.biombioe.2016.04.002.

[26] MoFECCEthiopia Forest Sector Review, Ministry of Environment, Forest, and Climate Change, Addis Ababa, 2017.

[27] MoFEDEthiopian National Accounts: Concepts, Sources, and Methods, Ministry of Finance and Economic Development, Addis Ababa, 2012.

[28] MoWIEEnergy Balance 2017/18, Ministry of Water, Irrigation, and Electricity, Addis Ababa, 2019.

[29] NBEAnnual Economic Report: 2019/20, National Bank of Ethiopia, Addis Ababa, 2021.

[30] D. Negash, A. Abegaz, J.U. Smith, H. Araya, B. Gelana, Household energy and recycling of nutrients and carbon to the soil in integrated crop-livestock farming systems: a case study in Kumbursa village, central highlands of Ethiopia, Glob. Change Biol. Bioenergy 9 (2017) 1588–1601, doi:10.1111/gcbb.12459.

[31] I. Owusu-Agyeman, E. Plaza, Z. Cetecioglu, Wastewater to Energy: relating Granule Size and Biogas Production of UASB Reactors Treating Municipal Wastewater, in: V. Naddeo, M. Balakrishnan, K.H Choo (Eds.), Frontiers in Water-Energy-Nexus—Nature-Based Solutions, Advanced Technologies and Best Practices For Environmental Sustainability, Springer, Cham, 2020, pp. 317–320.

[32] T. Pacetti, L. Lombardi, G. Federici, Water-energy Nexus: a case of biogas production from energy crops evaluated by water footprint and life cycle assessment (LCA) methods, J. Clean. Prod. 101 (2015) 278–291, doi:10.1016/j.jclepro.2015.03.084.

[33] H. Sanbata, A. Asfaw, A. Kumie, Indoor air pollution in slum neighbourhoods of Addis Ababa, Ethiopia, Atmos. Environ. 89 (2014) 230–234, doi:10.1016/j.atmosenv.2014.01.003.

[34] S. Seyoum, *The Economics of Biogas Digester*. International Livestock Centre for Africa, The Economics of Biogas Digester, International Livestock Centre for Africa, Addis Ababa, 1988.

[35] SNV, Bio-digester: A Worthwhile InvestmentBio-digester: A Worthwhile Investment, SNV-Ethiopia, Addis Ababa, 2017 Unpublished Report.

[36] SNV, Household Bio-Digester Cost Increase and Adjustment of Mason/BCE Payment and Investment IncentiveHousehold Bio-Digester Cost Increase and Adjustment of Mason/BCE Payment and Investment Incentive, SNV-Ethiopia, Addis Ababa, 2021 Unpublished Report.

[37] K. Teka, Y. Welday, M. Haftu, Analysis of household's energy consumption, forest degradation and plantation requirements in Eastern Tigray, Northern Ethiopia, Afr. J. Ecol. 56 (2018) 499–506, doi:10.1111/aje.12483.

[38] United Nations, Goals 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation, 2015 Available at https://sdgs.un.org/goals/goal9. Accessed on July 10, 2021.

[39] WBAThe Contribution of Anaerobic Digestion and Biogas towards Achieving the UN Sustainable Development Goals, World Biogas Association, 2016 Available athttps://www.worldbiogasassociation.org/ Accessed on June 20, 2021.

[40] G. Zelleke, G. Agegnehu, D. Abera, S. Rashid, Fertilizer and Soil Fertility Potential in Ethiopia: Constraints and Opportunities for Enhancing the System, International Food Policy Research, Washington D.C., 2010.

[41] M. Abdel-Aal, I. Haltas, L. Varga, Modelling the diffusion and operation of anaerobic digestions in Great Britain under future scenarios within the scope of water-energy-food nexus, Journal of Cleaner Production 253 (2020) 119897, doi:10.1016/j.jclepro.2019.119897.