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Article

Bio-Wastes as an Alternative Household Cooking Energy Source in Ethiopia

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Abstract: Up to the present day, wood has been used to supply the needs for cooking in rural Africa. Due to the ongoing deforestation, households need to change to other energy sources. To cover this need, a large amount of people are using residues from agriculture (straw, manure) instead. However, both straw and manure also have a function in agriculture for soil improvement. Using all the straw and manure will seriously affect the food production. In this paper we first determine the amount of energy that households need for cooking (about 7 GJ per year). Then we estimate the amount of residues that can be obtained from the agricultural system and the amount of energy for cooking that can be derived from this amount when different conversion techniques are used. The amount of residues needed is strongly affected by the technology used. The traditional three stone fires require at least two times as much resource than the more advanced technologies. Up to 4 ha of land or 15 cows are needed to provide enough straw and manure to cook on the traditional three stone fires. When more efficient techniques are used (briquetting, biogas) this can be reduced to 2 ha and six cows. Due to large variation in resource availability between households, about 80% of the households own less than 2 ha and 70% holds less than four cows. This means that even when modern, energy efficient techniques are used the largest share of the population is not able to generate enough energy for cooking from their own land and/or cattle. Most rural households in Sub-Saharan Africa may share similar resource holding characteristics for which the results from the current findings on Ethiopia can be relevant.

Keywords: energy demands; bio-wastes; conversion technology; resources holding; cooking; rural Africa

1. Introduction

Access to modern energy services remains an issue for poor people in developing countries. In Ethiopia about 83% of the population does not have access to electricity and 93% uses biomass-based energy for cooking, which surpasses 99% in rural areas [1,2]. Firewood is the main fuel followed by crop residues and cows dung collected from common resource pools or own resources. This situation is typical for many regions in Sub-Sahara Africa [3].

Assessments conducted on availability of wood fuel in the 1970s and 1980s have been published with controversial results ignoring the actual supply and demand gaps [4]. Nowadays, this is a major concern since firewood or charcoal produced from common resource pools also serve as a means of income to poor rural and urban households. Urban households who are unable to afford modern energy supply rely on energy from biomass for cooking [5]. The biomass comes from rural resources through purchasing—creating a link between urban and rural. For instance, about 84% of the urban population in Ethiopia uses energy from biomass for cooking [1], about 45% uses purchased firewood. This indicates a heavy dependence of both rural and urban on common resource pools for both fuel and income. Therefore, common resource pools became scarce and people travel long distances to collect firewood. This imposes heavy burden on women and young girls who are traditionally charged with household activities. In addition, the use of common resource pools is becoming an issue due to increasing legislation regarding natural resources protection and privatizations. When firewood is scarce and common resource pools are restricted, people shift to their own resources [4,6]. However, it poses hardship for poor households with insufficient land resources, unable to produce enough for themselves [6,7]. Land is a key resource for any form of biomass-based energy directly extracted from virgin sources or product processing.

One of the means to reduce dependence on traditional use of biomass energy is to promote and supply energy efficient technologies [2,6]. Currently, most rural households use inefficient stoves for cooking. There are several biomass stoves available with different sizes, designs and efficiencies [8,9]. As in other developing countries, there is a process of modern energy promotion in Ethiopia stressing the need for improved biomass stoves for baking local foods, the so called "Injera". There are also modified charcoal burning stoves available on the market. Most of these stoves are not sufficiently promoted and distributed to rural areas. They are designed to burn firewood or charcoal better than the traditional three-stone open fires [8,9]. Efficient wood burning stoves rely on the availability of firewood, so they cannot be a sustainable solution. There are better stoves, but they do not use just biomass directly; require transformation of biomass into other forms like briquettes and biogas. Briquetting and biogas technologies have long been recognized as a solution for rural developing countries cooking energy issues. It contributes to limiting deforestation [10] perhaps as a solution beyond the year 2030 as proposed by the International Energy Agency (IEA) [2]. Both briquetting and biogas technologies are viable to improve the efficiency in traditional stoves by a factor of two to six [11,12]. Bio-wastes from crop residues and cattle dung could be a suitable feedstock for applying these technologies.

Several studies show the availability of bio-wastes in developing countries. The global potential energy of agricultural residues has been studied very well [13–15]. There are also several country specific studies on availability of biomass energy resources in Sub-Saharan Africa [16–18]. These studies show the general overview of the national potential that could be harnessed from available resources. Availability of bio-wastes for household energy depends on the household resources (lands and livestock) holding [6], and competing purposes, like for feeding and soil mulching [19]. However, use of improved biomass energy technologies like biogas requires sufficient substrates. This is evidenced with family biogas digesters installed in Sub-Saharan facing operational problems due to a shortage of substrates [20]. A report from the survey in Uganda and Ethiopia also revealed similar problems *i.e.*, over 50% of the installed family biogas systems in the survey areas were not functioning due to factors attributed to insufficiency of substrates [21,22]. This implies the existence of a huge discrepancy between the nationally available potential and the practically implementable potential of households. If sufficient bio-wastes are not available at households, promotion and installation of improved biomass energy conversion technology like biogas cannot be an option. This means that investments in energy saving technologies are useless when it turns out that there is not enough biomass available. So, first determining the availability of biomass is needed. To the best of our knowledge no studies have yet addressed the availability of bio-wastes for improved biomass energy technologies in households in developing countries.

The present paper aims to determine the availability of bio-wastes for household cooking energy needs. We use a bottom-up approach as a guiding principle considering household resource holdings and improved biomass energy conversion technologies. The purpose of the study is to determine whether there is sufficient biomass at households. If the available biomass is not sufficient for the demand, making an economic analysis does not make sense. Thus, analysis on the economic capacity of the households to adopt improved energy conversion technologies and related costs are not addressed in current study. The results from the study will provide an insight in the extent to which bio-wastes may contribute to rural cooking energy demands if improved biomass energy conversion technologies are taken into account. The remaining part of the paper is organized as follows. Section 2 presents methodology used for the study. In this section first the systems studied are described and then the significant characteristics of the system studied (demands, waste streams and thermal efficiency of conversion technologies) are determined. In Section 3, the results of the study are presented and discussed in Section 4. Finally, concluding remarks are presented in Section 5.

Background of the Country

Ethiopia is located in the horn of Africa between 3 and 15 degrees northern latitude and 33 and 48 degrees eastern longitude covering a land area of about one million square kilometer (1×10^6 km^2). About 340,000 square kilometers are used for agriculture, of which about 140,000 square kilometers is arable land and 200,000 square kilometers is permanent pasture. About 120,000 square kilometers of arable land is used for temporary crops where the remaining is used for permanent cash crops. More than 50% of the total land area is categorized as other land which is not suitable for farming (see FAO definition). Forest area accounts for 12% (120,000 square kilometers) of the total land areas [23]. About 52% of the land area lies between hot and temperate climate suitable to grow various kinds of crops [24]. The country has diversified climates ranging from semi-arid desert type in the lowlands to humid and warm (temperate) type in the highlands with a range of mean annual rainfall distribution of below 300 mm to over 2000 mm. There is no clear distinction between seasons in Ethiopia, but based on rainfall, December to February are categorized as dry season and June to August as wet season. The wet season is when most of the rain-fed agricultural production is performed. Most of the production is performed by small scale private farmers for subsistent food consumption, whereas commercial production constitutes about 3% [25]. Ethiopia has a population of about 90 million, of which more than 70 million live in rural areas [26].

2. Methodology

2.1. Description of the System Analyses

In the present household energy system, firewood is used in traditional stoves [1]. Collection of firewood is restricted by scarcely available common resource pools. As a result bio-wastes are increasingly being used as a substitute. Bio-wastes come from household resources (land and livestock). Land use accounts for crop production. When crops such as maize and wheat are harvested residues remain in the form of straw, stalks or husks. Residues can be classified as primary and secondary residues or harvested and processed residues respectively [15]. Primary or harvested residues refer to residues produced and remain on crop land when crops are being collected. Secondary or processed residues result from crop processing. Residues are not resources without value. When firewood and feed are scarce they are used for fuel and feeding. When construction materials are scarce residues are used for construction purposes like thatching. Some residues remain on the land to improve soil quality and prevent soil erosion. When residues are removed for energy purposes the other uses are affected. So, adjustment is needed regarding the amount available for energy. Similarly, livestock are held to provide food products like milk and meat. These commodities are produced when livestock feeds on available biomass, and the amount left unconverted is produced as dung. Livestock produces dung while on the range or in pens. Dung produced on the range is not easily accessible for collection. In practice only dung produced in the pens during the night can be collected and used for different purposes. When firewood is scarce dung is used for fuel otherwise used as manure to improve soil quality. Using all available dung for energy purposes affects soil fertility. Thus the amount of dung available for energy needs to be adjusted.

Bio-wastes in particular crop residues are a loose biomass. Loose biomass is not suitable to use for energy purposes due to its fast burning rate, and problems with transportation and storage. Conversion into different energy carrier forms is required to improve its suitability and energy yield. Several possible biomass energy conversion technologies can be used. Most of these technologies are less feasible for rural household cooking energy applications. The improved biomass energy conversion technologies considered in this study are briquetting and biogas systems. These technologies are sufficiently mature to be applied in rural developing countries.

Briquetting can be defined as the process of increasing the volumetric energy density of the biomass through compaction [27]. The biomass density increases as its level of extrusion increases. Briquette production involves grinding, sieving, mixing, molding and drying operations. Loose biomass like residues requires densification to make it suitable for energy applications. In the process, the volumetric energy density of the biomass increases as well as its burning time. Thermal carbonization can be applied to convert briquettes into charcoal, which can further increase its calorific values. Briquettes can be used in any biomass stove including traditional three stones open fire (TSF). When used in traditional stoves most of the energy contents dissipate, unused to the surrounding atmosphere. Using improved stoves increases energy gain due to increased thermal efficiencies of the stoves. Energy saving can be achieved from both densification processes and stoves' thermal efficiency improvement.

A biogas system can be defined as a process of converting biomass containing highly volatile organic matter into biogas in an oxygen deficient environment by means of anaerobic bacteria. Residues and cow dung contain high amounts of volatile organic matter capable of being converted to biogas. A biogas system has two main components: the anaerobic digester (AD) and the stove. Biomass is converted to biogas in an AD and then connected to the stove to provide thermal energy for cooking services. When converted to biogas some portion of the biomass is left unconverted and is removed as slurry. During combustion some of the heat energy dissipates to the surrounding atmosphere and all heat cannot be used for cooking. A biogas stove has a thermal efficiency similar to liquid petroleum gas (LPG) stoves. Much energy saving can be achieved by the physical and chemical transformation of biomass to a more energy dense form (methane) and by improving the thermal efficiency of the stoves.

In the analyses, the interactions between the two waste streams are not considered. For instance, in the resources competition, a part of the residues goes to feeding. When residues are being fed to livestock the resulting dung can provide higher biogas energy yields. Applying dung to the soil can increase crops yield which in turn increases the amount of residues. Co-digestion of the two waste streams also increases the quantity and quality of biogas yields. These are not addressed in the current study due to the lack of data on co-holding and complexity of the analysis. The two waste streams are analyzed and presented independently. Bio-wastes produced from crop processing at households are excluded because of their low quantity. Bio-wastes from other livestock animals are also not considered because of their holding situation and resulting low dung yield. Primary crop residues and cow dung are produced in large amounts and frequently used for cooking energy purposes and therefore they are included in his study.

2.2. Determining the Study Assumptions

2.2.1. Energy Demand for Cooking

Households in rural developing countries, particularly Sub-Saharan Africa, mainly need energy for cooking, lighting and empowering of low voltage elementary appliances. Lighting and empowering of elementary appliances require relatively low amount of energy which can be satisfied with electricity from photovoltaic cells [28]. Over 90% of the rural household energy is required for cooking, but also very challenging to meet [2,28], thus considered for this study. The amount and type of energy used for cooking in rural developing country depends on income, availability of fuel, cooking behavior and efficiency of the appliances [29,30]. The composition of fuel types determines the amount of biomass energy used by households. The energy ladder model states that the composition of fuel increases with relatively less biomass energy when households' income increases [30]. However, variation in fuel composition is very rare in rural areas where biomass is the sole source of energy for cooking. The effect of family size, cooking behavior and types of food the family cooks has been neglected. This is based on the assumption that rural households cook unprocessed food, light fires two to three times daily to cook food for the family and that they cook mostly similar foods based on prevailing culture. It is obvious that large families cook large amounts of food but the corresponding variation in the amount of biomass used in cooking is considered negligible. Significant differences could be attributed to variation of stove efficiencies. Households that can afford efficient stoves could have an advantage in using smaller amounts of biomass for equal amounts of final energy for cooking. Therefore an average amount of final useful energy (thermal energy) required for cooking is assumed for households with an average family size of about six persons. This helps to reduce variation in the households' energy demand since there are similar amounts of thermal energy required to cook food.

Moreover, data on the rural household energy consumption pattern and demand is not available for Ethiopia. We decided to derive from the national biomass energy use data based on [10] taking a traditional conversion efficiency of 10% into account. The estimation considered the national primary energy consumption of the country's presented in [28]. The amount of primary biomass energy consumed in the year in 2012 was about 1.2 EJ (1.2×10^{18} J). About 100% of the rural and 85% of the urban households used biomass energy for cooking [1]. The amount of biomass energy used is assumed to be about 70 GJ (70×10^{9} J) per household corresponding with about 7 GJ of net useful energy. Some area specific studies in rural areas of the country also show an annual consumption of 3–5 tons per household [31,32], which corresponds to about 5–8 GJ of useful energy. A World Bank working paper suggests a household's annual use of 5 GJ of useful energy as a benchmark for measuring living standards in developing countries [33]. In this study we assume an average annual net useful energy demand of 6 GJ for cooking based on the aforementioned literatures. This is an equivalent daily consumption of about 16 MJ or 10 kg of oven-dry biomass if used in traditional three stone open fires. It is the amount of energy assumed to be sufficient to heat or cook food for households having average family sizes of six whatever technologies are used. Hereafter, demand refers to cooking energy demands.

2.2.2. Thermal Output of the Conversion Systems

Thermal output can be defined as the final useful energy directly delivered to food for cooking. The thermal output of the stove depends on the type of fuel used and its burning efficiency. For instance, a TSF using air dried wood fuel provides low thermal energy due to moisture content of wood and low stove conversion efficiency. Some of the heat energy dissipates in removing its moisture content and some heat dissipates to the surrounding atmosphere. A kilogram of oven-dried biomass theoretically contains a calorific value of about 17–22 MJ (1 MJ = 10^{6} J), but it decreases with increasing moisture contents [34]. The lower heating values of different crops residues vary from 13–19 MJ/kg [34,35]. In this study, the moisture content is set to air-dried weight with the average moisture content of about 20% typical of biomass used in rural areas. We assume a lower heating value of 15 MJ/kg taking the moisture content and variation among crops residues into account. The TSF is an open air system where most of the heat energy dissipates to surrounding air during cooking. Only about 8%–12% of the energy content is obtained for cooking [11]. The combined heat loss due to moisture content and burning inefficiency is huge when only about 1.5 MJ of useful energy per kilogram of biomass is left for cooking.

More biomass saving can be achieved with Improved Stove burning Briquettes (ISB) [11,12]. Briquetting increases the energy density of the residues by a factor of five to ten [27,36]. The calorific value of briquettes varies from 14–19 MJ/kg based on the type of residues and its level of compaction [27,37]. Further calorific increments can be achieved through a process of thermal carbonization to over 30 MJ/kg [38]. Thermal carbonization increases its calorific value due to reduction of hydrogen and oxygen content in the process. A kilogram of briquette combusted in improved biomass stoves with a thermal efficiency of 20% can provide about 3.8 MJ of useful energy for cooking. We assume that briquettes are produced manually and do not require electrical energy input.

Biogas production involves four phases of digestion processes where different species of microorganisms are involved [39]. These processes are essential to obtain a biogas with high energy values. Theoretically, biogas is a mixture of 60%–75% CH_4 and 40%–25% CO_2 [39] with a calorific value of about 20–25 MJ/m^3 [34]. A wide range of biomass from different waste streams can be used as feedstock. However, their biogas yield and methane content varies with several process conditions and feedstock compositions. For instance, a theoretical biogas yield of biomass varies with the contents of carbohydrate, protein and fat, which is between 0.700 m^3 to 1.250 m^3 per kg of total solids [40]. The compositions of these nutrients among different biomass sources are essential for the methane content determining final thermal efficiency of the system. The variation in the biogas yield of cows dung is therefore influenced by the type of feed and digesters' process conditions [39]. Accordingly, the biogas yield of 0.180–0.380 m^3/kg of dry dung has been reported from cattle dung in developing countries [41–44]. In this study a biogas yield of about 0.280 m^3/kg of dry dung is assumed taking into account literature data and livestock condition of the country. Biogas production from agricultural residues is not as popular as using cow dung. Therefore little data is available on its biogas yield as a single feedstock. The nutrient composition of agricultural residues and its biogas yield varies widely even among cereal crops residues [40]. A biogas yield of 0.188–1.0 m^3/kg of cereal crop residues has been reported from different literature sources [18,45,46]. Most frequently reported yields are between 0.3–0.6 m^3/kg [45,47]. Given these literature data and the low digestibility potential of residues this study assumes a biogas yield of 0.400 m^3/kg of residue. Use of biogas for cooking requires specially designed stoves. The thermal efficiency of the stove is similar to that of LPG stoves, which is about 55%–60% [11,33]. In the process of conversion (in the digesters and stoves) a certain amount of energy inevitably dissipates to the atmosphere or is left unconverted. Hence, based on the average biogas yield and stoves conversion efficiency, about 4.8 GJ and 3.4 GJ of useful energy per ton of dry residues and dung respectively, is assumed for cooking. Table 1 presents the thermal output of different conversion technologies with varying bio-wastes.

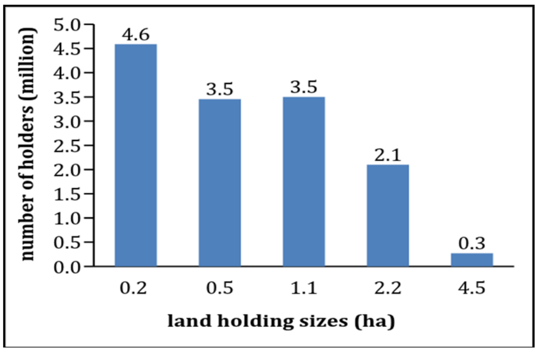
Table 1. Thermal output of the energy conversion systems with different bio-wastes.

Stoves	Technology	Feedstock	LHV (GJ/t)	Efficiency (%) [b]	Thermal output (GJ/t)
TSF	traditional	residues or dung	15	10	1.5
ISB	briquetting	residues	19	20	3.8
Biogas	AD	residues	8.8 [a]	55	4.8
Biogas	AD	dung	6.2 [a]	55	3.4

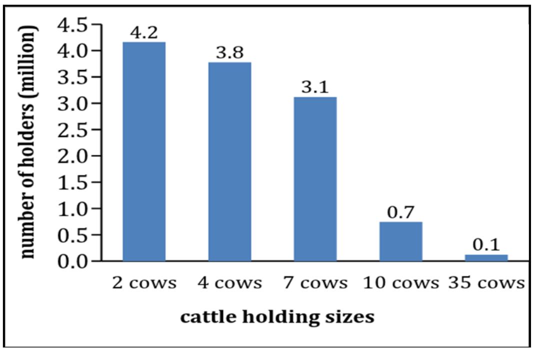
[a] own calculation based on specific biogas yield and its calorific value per m^3; [b] based on [11]; LHV = Lower Heating Value; TSF = Three Stones open Fire; ISB—Improved Stove burning Briquettes.

2.2.3. Availability of Bio-Wastes

The data on land and cattle holding and yields of crops are obtained from the Ethiopian Central Statistical Agency (CSA) [25]. The data on crop yield used for the current study has been cross-checked with FAOSTAT data for its consistency, but no significant differences were found. Data on household land tenure and cattle holding category is presented in Figure 1a,b. There is a modest regional and huge inter-household variation on land and cattle holding sizes. Regions with large areas of land, like Oromia regional state, on average hold about five cows, whereas Amhara regional state, with a higher population density per acre of land, on average holds four cows [21]. Lands used for agricultural production, for both arable and permanent pasture, represent only 34% of the total land area. A large proportion of the country's land (about 52%) is categorized as other lands, which is made up of degraded, marginal and built lands [23]. The national average land holding size is about 0.9 hectares (9000 m^2) and average cattle holding size is four cows. The analysis on energy potential in this study has taken an average national holding and specific household holdings. The energy potential from biomass is divided into four types as theoretical energy, technical energy, economic energy and achievable energy potentials [15,48]. Theoretical (gross) potential refers to the amount of energy produced from available biomass resources (land and cows) taking their gross heating value into account. Technical (available) potential refers to the fraction of gross potential available for energy, taking other competing purposes into account. The last potential, and the focus of the current paper, is the achievable potential which is calculated from the available resources actually used for cooking, taking into account conversion efficiencies. The economic potential is not considered here.



(**a**)



(**b**)

Figure 1. Households biomass resources holding sizes based on data from [25]. (**a**) Land holding; (**b**) Cattle holding; households are grouped based on the average size of holdings.

Ethiopia is among the top four cereal producing countries in Africa [13,23]. "Teff", maize, wheat, sorghum, barley and millet are the main cereal crops covering more than 80% of the crops land. Teff and maize accounts for about 40% of the main cereal crops produced in the country. The annual yield of cereal crops in the country is very low, between 1.5 t to 3.0 t per hectare (1 t = 10^3 kg). The annual yields of crops directly determine their corresponding quantity of residues (Table 2). The amounts of field-remaining residues are determined based on the values of residues to product ratios (RPR) of specific crops [34]. The RPR of cereal crops available in literature varies significantly [49]. The RPR used for this study is obtained from relevant literature (Table 2). After crops are collected residues ideally remain on the land as waste and are burnt to add value to the next crop production. In time of scarcity residues are used for feeding, fuel and construction purposes. Nowadays residues are one of the promising biomass energy resources that can be converted to liquid, gas and electricity to contribute to growing energy demands. But removing residues for energy involves a lot of environmental problems. Residues remaining on the land provide a lot of benefits. They prevent soil erosion, increase soil porosity, increase the soil carbon pool, facilitate nutrient recycling and help water infiltration [50]. The amount remaining for this purpose depends on weather conditions, crop rotation, existing soil fertility, slope of the land and tillage practices. Thus, the amount sustainably removed for energy varies from 30%–70% [49]. Most studies suggest a maximum of 30% removal or leaving a minimum of about 2 tons per hectare to prevent soil loss due to erosion [14,50]. Scarlat *et al.*, used the sustainable removal rate of 40% for wheat and barley, and 50% for maize and rice for the assessment of agricultural crops residues in the European Union [49]. The problem is serious for lands in tropical climate with poor quality, poor management and low inputs where subsistent farmers use extractive farming. Removing a ton of cereal crop residues is equivalent to a loss of about 40 kilogram of essential nutrients [50]. Losing such an amount is a huge problem for countries like Ethiopia with high rate of annual essential nutrient losses [51]. But, it is a usual practice in Asia and Africa to remove crop residues for fuel, forage and other purposes. In Ethiopia up to 85% of the crop residues are removed for fuel and feeding: Teff, wheat and barley straw for feeding, and maize and sorghum stalks for fuel and construction purposes [51,52]. It is apparent that crop residues are an essential component of an agricultural system requiring a balance between the use for land covering and energy. Taking these situations into account, we assumed about 30% removal of residues for energy. Thus, the available residues at households are calculated by multiplying the average tenure size (ha) by average crops yield (t/ha), RPR of specific crops and availability coefficient (%). The yield of cereal crop residues and their available fraction is shown in Table 2.

Table 2. Estimated available crops residues for energy based on [25,34].

Crops	Land area (Mha)	Crop yield (t/ha)	RPR	Residues (t/ha)	Available residues (t/ha)	Available residues (mt)
Teff	2.8	1.8	2.3	4.1	1.2	3.3
Barley	1.0	1.8	1.3	2.3	0.7	0.7
Wheat	1.6	2.1	1.3	2.7	0.8	2.3
Sorghum	1.9	2.1	1.5	3.2	0.9	1.7
Maize	2.0	3.0	1.4	4.2	1.3	2.6
Finger millet	0.4	1.8	1.3	2.3	0.7	0.3
Other crops *	2.4	1.5	1.3	2.0	0.6	1.4
Total/ave.	12.0	2.0	1.5	3.0	0.9	11.0

* Other crops refer to non-cereal crops like pulse and oily crops, t = ton (1 t = 10^3 kg), ha = hectare (1 ha = 10^4 m^2), Mha = 10^6 ha, Mt = 10^6 t.

Ethiopia is among the top five countries with a large livestock population in Africa with 54 million cattle heads [23]. Livestock is an integral part of agricultural system of the country to serve as food, farming and as a means of income, and to provide their dung for manure and fuel [51]. Dung production of cows is affected by type, age, season of the year and availability of feed. Relevant data on dung production is not available for the country. A dry weight daily dung production of 2 kg per animal per day is estimated in this study based on [41,42,51], equivalent to annual yield of about 700 kg per animal (0.7 t/animal). Cattle are mostly range-fed, and about 40% of the produced dung is not accessible for collection [51]. Households collect dung for different purposes. When firewood is available dung is used for soil amendment otherwise it is used for fuel. It is essential to estimate the amount available for energy since the entire amount of dung cannot be collected and used. Relevant data on the amount available for energy is not available for the country. We introduced a 40% availability coefficient taking into account other competing purposes and based on relevant literature [51]. Thus, the available dung at household is estimated by multiplying the household average cattle holding size by annual dry dung amount (t/animal) and availability coefficient (%). The annual bio-waste production and its available fractions are summarized in Table 3.

Table 3. Summary of annual average production of bio-wastes and its available fraction.

Bio-wastes	Annual yield	Unit	Availability factor	Annual available yield	Unit
Residues	3.0	t/ha	0.3	0.9	t/ha
Dung	0.7	t/cow	0.4	0.3	t/cow

2.2.4. Driving the System Relationship

In Section 2.2.1 the household's annual demands in terms of thermal energy required for cooking is determined. Thus, households annually require about 6 GJ of useful energy for cooking. However, the amount obtained as thermal energy for cooking depends on the efficiency of the conversion processes (Table 1). This varies from 10% in traditional stoves to more advanced biogas stoves having 60% conversion efficiency [11,53]. The amount of thermal energy obtained based on the conversion efficiency of the stoves determines the amount of bio-waste required for the demands. Specific bio-wastes (residues or dung) required for the demands are calculated in terms of thermal outputs of the stoves. If households use improved technologies, less resources are required to provide the energy required for cooking. The available bio-wastes are fixed, while thermal outputs of the stoves vary with increasing efficiencies. Meeting the cooking demand requires bio-wastes produced from agricultural lands or cows (Table 3). The amount of these resources (land and cattle) required to meet the demand are then determined based on the annually available yields of bio-wastes. These resources are unevenly distributed among households (Figure 1a,b). Thus, availability of bio-wastes for cooking energy demand at households is therefore determined by connecting the required resources (based on conversion technologies) to households' resource holding sizes. If the ratio of supply to demand for households is more than one, the available bio-wastes are assumed to be sufficient and can be considered as alternative cooking energy source.

3. Results

3.1. Resources Required to Meet the Households' Demands

With the data derived in Section 2.2 the resources required to meet the households' demands with different conversion systems can be calculated. The data is presented in Table 4. The data refers to a household's annual demand with varying conversion technologies. Each household annually requires about 5–7 GJ of useful energy for cooking. With a traditional stove of low thermal output, households annually need about four tons of bio-waste to meet their demands. To produce this amount of bio-waste about 4.4 ha of land or 15 cows are required. It implies that large amounts of resources are required to compensate for the energy lost in the conversion processes. Conversion of residues to briquette and use in improved stoves increase efficiency. As a result the amount of residues required for the demand is reduced to 1.6 tons and the corresponding land area to about two hectares. More biomass savings can be achieved when bio-wastes are converted to biogas. About 1.2 tons of residues or 1.6 tons of dung is required to meet the demand. Their production requires about 1.3 hectares of land or six cows.

Table 4. Biomass resources required to meet the demand with different energy conversion systems.

Conversion technologies	**Households biomass resources required to meet the demand**			
	Residues (t)	**Land (ha)**	**Dung (t)**	**Cows**
TSF	4.0	4.4	4.0	15
ISB	1.6	1.8	-	-
Biogas	1.2	1.3	1.6	6

3.2. Availability of Resources to Meet the Households' Demand

As mentioned earlier the average landholding sizes in Ethiopia is 0.9 hectares and on average households keep four cows. If we compare this with the resources needed (Table 4), it becomes clear that the average household has not enough land or cows to provide enough residues or dung to generate enough energy for cooking even if they use the most advanced technologies to do so.

A huge variation in holding sizes exists between households (Figure 1). Tables 5 and 6 show the distributions of land and cattle over the households. Only 5% of the households have enough land or cows to generate enough cooking energy using the traditional cooking methods (three stone fire). When briquetting or biogas is used about 40% of the households can generate enough energy.

A closer look at Tables 5 and 6 shows the large difference between the gross energy and the useful energy. The gross energy is based on the total amount of residues produced (straw, manure). The gross energy is over 10 times as large as the useful energy. As a result for all households the gross energy is enough for cooking. However since not all residues can be used for energy purposes (straw is needed for soil protection *etc.* as mentioned in the methodology section) and due to the fact that a lot of energy is lost in the conversion process, the actual energy that can be obtained from residues is far less than the gross energy.

Table 5. Households' (hh) annual energy production potential from crop residues.

Tenure size	Land (10^6 ha)	Households (10^6)	Holders (%)	Average holding (ha/hh)	Residues (ton/hh)		Potential energy (GJ/hh)		Useful energy per hh (GJ)	
					gross	available	gross	available	briquette	biogas
0.1–0.5	0.7	4.6	33	0.2	0.5	0.1	9	3	0.6	0.7
0.51–1.0	1.9	3.5	25	0.5	2	0	29	9	2	2
1.01–2.0	3.9	3.5	25	1.1	3	1	59	18	4	5
2.01–5.0	4.5	2.1	15	2.2	6	2	117	35	7	9
5.01–8.0	1.0	0.2	2	4.2	13	4	227	68	14	18
8.01–11	0.2	0.03	0.2	8.5	25	8	458	137	29	37
total/ave	12.2	13.9	100	0.9	3	1	48	14	3	4

Table 6. Households (hh) annual energy production potential from cow dung.

Cattle holding size	Cattle (10^6)	Holders (10^6)	Holders (%)	Cattle per hh	Dry dung per household (tons)		Potential energy (GJ/hh)		Useful energy
					gross	available	gross	available	biogas (GJ/hh)
1–2	6	4	35	2	1	0.4	19	8	1
3–4	13	4	32	4	2	1	44	18	3
5–9	22	3	26	7	5	2	88	35	7
10–19	7	1	6	10	7	3	120	48	9
20–49	4	0.1	1	35	24	10	435	174	33
Total/av	53	12	100	4	3	1.2	56	22	4

4. Discussion

4.1. Opportunities and Challenges of Using Bio-Wastes as Cooking Energy Sources

Our results show that, when improved biomass energy conversion technologies are used, fewer resources are required to produce bio-wastes that are needed to meet the households' energy demands. Huge benefits can be gained from residue briquetting and using improved stoves that provide a uniform combustion rate, reduces possible spontaneous combustion and emissions of particulate matter [12]. More resource savings are achieved when bio-wastes are transformed into biogas. Transformation of bio-wastes into biogas also provides an advantage of resource use-efficiency where biogas slurry can be used for soil improvement. Although competition for resources is involved, production of bio-wastes does not require extra land and imposes no extra pressure on natural resources (forests). The relative benefits of using bio-wastes as a source of energy for cooking are clear from the perspective of resource use efficiency and reduction of environmental impacts. However, several constraining factors are involved when using bio-wastes as an alternative cooking energy sources.

We made a separate analysis for the availability of crop residues and cow dung due to the lack of data on co-holding of land and cattle. The interdependency of land and cattle holdings could be high in areas where a range-fed system is dominant. Traditionally, common resource pools are used for herd grazing, but nowadays this is less likely to occur due to land ownership and privatizations. Households with large areas of land will have the possibility to use part of their land for grazing [51]. As the data shows about 85% of the households on average hold less than 1 ha of land, which is probably not enough for both crop production and grazing. When land and cattle holdings are compared, about 2 million households do not have cows and large numbers just have few (Figure 1a,b). Most of the cattle resources are held among few of the households presumably with large tenure sizes. Although cow dung and crop residues account for the major part of agricultural wastes that can be used to reduce rural households' energy demand for cooking [11], most households do not have sufficient resources to produce the wastes. This is partly related to the historical land ownership with families passing over ownership across generations through inheritance. Available agricultural lands are limited and the amount of land in households is diminished when the family grows and subsistent farming continues with low inputs. Availability of bio-wastes for energy is further constrained by competing purposes. Previous studies have considered varying the availability of bio-wastes for energy [13,14]. The amount available for energy purposes can be attributed to practical and environmental aspects of the local situation. If the environmental impact of removing bio-wastes is considered as indicated in the literature [50], no residues can be available for energy. In areas where the resource scarcity prevails and mixed farming systems are dominant, the likelihood of using residues for land covering is low. Countries with dense livestock populations in Sub-Saharan Africa and south Asia use more than 60% of their cereal crop residues for feeding and less than 20% is left for soil mulching and fuel [54]. The situation is relevant to the current study area where households depend on bio-wastes for different purposes. About 85% of the produced residues are removed for feeding, trading and fuel [51,54]. Taking this into account we considered 30% of the residues available for energy purposes, but even doubling this amount cannot help households to meet their energy demand. When stringent land scarcity is accompanied by heavy competition, particularly in areas with mixed farming systems, the availability of crop residues as an alternative energy source for cooking is less likely. Seasonal variability of residues also can hinder their continuous use, since residues are only available for a few months during the crop harvesting season. This can be the main constraint for most rural households depending on a rain-fed production system producing crops once in a year. Otherwise, households need to store their residues for a continuous supply of their energy sources. In particular the utilization of biogas technology requires a constant supply of biomass for consistent production. However, the low density of residue makes it difficult to store [12]. The seasonal availability of residues needs to be seriously considered since households may not have sufficient places to store them.

Application of renewable energy technologies depends on the type of resources. This requires better understanding of the technological differences between biomass energy and other renewable energy applications. Application of other renewable energy technologies, like solar PV, wind turbine and hydropower, need naturally existing resources. Such resources are more or less in constant supply regardless of their seasonal intermittences. Of course, application of improved biomass energy conversion technologies, like biogas, also requires availability of sufficient bio-wastes derived from produced resources. If households are unable to produce and supply enough, it is unlikely that the plant works continuously. During the last two decades millions of family scale biogas digesters have been installed in most Asian countries, with leading installations in China and India [42]. Most sub-Saharan African countries also followed in their footsteps and developed national biogas projects as rural energy strategies. Several donor organizations, in partnership with countries' governments, are working on the installation of the digesters. African Biogas Partnership Programs (ABPP) is one of the programs actively involved in the installation of family biogas digesters in six Sub-Saharan African countries, namely Kenya, Burkina Faso, Ethiopia, Tanzania, Uganda and Senegal in two phases. The first phase was between the years 2009–2013 when Ethiopia planned to install 14,000 biogas digesters, out of which 57.6% is achieved [55]. The installation of the digesters is based on the subsidy schemes where about 60% of the total costs (about 8,000 ET birr) are born from the households [55,56]. The feasibility assessments for the program require households to have at least four cows [21]. The dung from four cows could be sufficient to meet the demand if all the produced dung is collected for energy purposes. In reality, all the produced dung cannot be available to run the system sustainably due to factors attributed to collection and competition for dung. This can help us to understand how the present family biogas digesters are unable to solve rural households' energy problems in most Sub-Saharan Africa countries [20]. More scarcity could be expected if the national average resources are considered in the feasibility assessments. Accessibility alone to improved technology is not enough to curb rural cooking energy problems. Thus, availability of resources to operate the technology is equally important taking into account specific household attributes (*i.e.*, holding and competing purposes).

4.2. Comparing the Results

As already presented in this study, several studies have been conducted to determine the bio-wastes energy potential in developing countries [13–15], including country-specific studies available in the literature [16–18,44]. Average national biomass yield data and its gross calorific values were generally used in the assessments. These studies mainly aimed to provide a general overview of the resource availability at large scales. Yields of crops are a detrimental factor for the amount of residues obtained. A future increase in crop yield in Sub-Saharan Africa is also expected to lead to an increase in the per hectare return of residues [57]. With current crop yields, one estimates an energy output of about 0–10 GJ/ha taking competing factors into account [14,57]. The national average energy yield per hectare in the current study (Table 3) is more or less in line with this. In reality there is huge gap between the quantity to be produced at national scale and the amount actually available for energy in households. The assessment at household level needs a different approach where specific assumptions relating to households are considered. The results of this study presented in Tables 5 and 6 clearly indicate the significance of various approaches. When national average data and gross calorific value of the biomass are considered from a top down perspective, the available bio-wastes are enough to satisfy the demands. Households can share about one ton of dry residues or dung if they have equal access to available bio-wastes. This amount is sufficient to provide twice their demand, which is misleading since it neglects actual implementation. Yields of residues can be increased with larger crops yields but this involves huge uncertainty regarding the amount available for energy due to the increased demand for feeding purposes [54].

This study stressed on the availability of energy from bio-wastes for cooking in households. Thermal efficiency of the cooking systems and resources owned by households form the base for our bottom up assessments. These two additional factors are important to assess the availability of resources required for the installation of standalone energy systems. The combination of the two factors clearly shows how households can be self-sufficient with their bio-wastes overcoming the existing constraints. However, with the improved technologies studied here, less than 30% of the available potential can be recovered for cooking due to losses in the conversion processes. The loss in conversion can surpass 90% in traditional conversion systems [11]. Therefore, less than 30% of the households are self-sufficient in meeting their energy demands, with improved technologies, when their resources and losses in conversion processes are considered. One of the major shortcomings of the top down approach is its inability to show the actual amount of resources households can have. It is obvious that potential for biomass energy can vary due to methodological differences [58]. However, the approach used for the current assessment is vital to indicate the availability of household resources of developing countries where the development of standalone energy systems is a priority. This study focuses on the household resource situation in Ethiopia which may be typical for other developing countries with similar socioeconomic situations.

5. Conclusions

Ethiopian rural households require about five to seven GJ of useful energy for the annual demands for cooking. This value is typical for most rural areas in developing countries. Up to the present, wood was used to supply the needs for cooking, but due to ongoing deforestation, households have changed to the use of agricultural residues (straw and manure) as an energy source. The resources needed to provide the cooking demands depend on the conversion technology used. Up to 4 ha of land or 15 cows are needed to provide enough straw and manure to cook on the traditional three stone fires. When more efficient techniques are used (briquetting, biogas) this can be reduced to 2 ha and six cows. This indicates that use of improved energy conversion technology studied here can help to achieve huge biomass savings of up 60%. However, a large variation in resource availability exists between households. 80% of the households own less than 2 ha and 70% holds less than four cows. This means that, even when modern, energy efficient techniques are used, the largest share of the population is not able to generate enough energy for cooking.

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Author Contributions

Gudina Terefe Tucho designed the study, performed the analysis and drafted the manuscript. Sanderine Nonhebel helped to design the study, preparation of the manuscript and made final review of the manuscript. All authors discussed the results and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. CSA. *Ethiopian Welfare Monitoring Survey Report of 2011*; Central Statistical Agency (CSA) of Ethiopia: Addis Ababa, Ethiopia, 2012.

2. IEA. *Energy for All: Financial Access for the Poor in World Energy Outlook 2011*; International Energy Agency (IEA): Paris, France, 2011.
3. UNDP. *The Energy Access Situation in Developing Countries: A Review Focussing on Least Developed Countries and Sub-Saharan Africa*; United Nations Development Programme and World Health Organization (UNDP): New York, NY, USA, 2009.
4. Arnold, J.; Köhlin, G.; Persson, R. Woodfuels, livelihoods, and policy interventions: Changing perspectives. *World Dev.* **2006**, *34*, 596–611.
5. Kebede, B.; Bekele, A.; Kedir, E. Can the urban poor afford modern energy? The case of Ethiopia. *Energy Policy* **2002**, *30*, 1029–1045.
6. Cooke, P.; Kohlin, G.; Hyde, W.F. Fuelwood, forests and community management—Evidence from household studies. *Environ. Dev. Econ.* **2008**, *13*, 103–135.
7. Gebreegziabher, Z.; Mekonnen, A.; Kassie, M.; Köhlin, G. *Household Tree Planting in Tigrai, Northern Ethiopia: Tree Species, Purposes, and Determinants*; Working Papers in Economics No 432; University of Gothenburg: Gothenburg, Sweden, 2010.
8. Jetter, J.J.; Kariher, P. Solid-fuel household cook stoves: Characterization of performance and emissions. *Biomass Bioenergy* **2009**, *33*, 294–305.
9. MacCarty, N.; Still, D.; Ogle, D. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy Sustain. Dev.* **2010**, *14*, 161–171.
10. Subedi, M.; Matthews, R.B.; Pogson, M.; Abegaz, A.; Balana, B.B.; Oyesiku-Blakemore, J.; Smith, J. Can biogas digesters help to reduce deforestation in Africa? *Biomass Bioenergy* **2014**, *70*, 87–98.
11. Bhattacharya, S.; Abdul Salam, P. Low greenhouse gas biomass options for cooking in the developing countries. *Biomass Bioenergy* **2002**, *22*, 305–317.
12. Werther, J.; Saenger, M.; Hartge, E.; Ogada, T.; Siagi, Z. Combustion of agricultural residues. *Prog. Energy Combust. Sci.* **2000**, *26*, 1–27.
13. Dasappa, S. Potential of biomass energy for electricity generation in Sub-Saharan Africa. *Energy Sustain. Dev.* **2011**, *15*, 203–213.
14. Kim, S.; Dale, B.E. Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy* **2004**, *26*, 361–375.
15. Smeets, E.M.W.; Faaij, A.P.C.; Lewandowski, I.M.; Turkenburg, W.C. A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog. Energy Combust. Sci.* **2007**, *33*, 56–106.
16. Duku, M.H.; Gu, S.; Hagan, E.B. A comprehensive review of biomass resources and biofuels potential in Ghana. *Renew. Sustain. Energy Rev.* **2011**, *15*, 404–415.
17. Jingura, R.M.; Matengaifa, R. The potential for energy production from crop residues in Zimbabwe. *Biomass Bioenergy* **2008**, *32*, 1287–1292.
18. Nzila, C.; Dewulf, J.; Spanjers, H.; Kiriamiti, H.; van Langenhove, H. Biowaste energy potential in Kenya. *Renew. Energy* **2010**, *35*, 2698–2704.
19. Ravindranath, N.H.; Somashekar, H.I.; Nagaraja, M.S.; Sudha, P.; Sangeetha, G.; Bhattacharya, S.C.; Abdul Salam, P. Assessment of sustainable non-plantation biomass resources potential for energy in India. *Biomass Bioenergy* **2005**, *29*, 178–190.
20. Orskov, E.R.; Anchang, K.Y.; Subedi, M.; Smith, J. Overview of holistic application of biogas for small scale farmers in Sub-Saharan Africa. *Biomass Bioenergy* **2014**, *70*, 4–16.

21. Eshete, G.; Sonder, K.; ter Heegde, F. *Report on the Feasibility Study of a National Programme for Domestic Biogas in Ethiopia*; SNV Netherlands Development Organization: Addis Ababa, Ethiopia, 2006.
22. Kariko-Buhwezi, B. Challenges to the sustainability of small scale biogas technologies in Uganda. In Proceedings of the Second International Conference on Advances in Engineering and Technology, Entebbe, Uganda, 31 January–1 February 2011.
23. FAO. FAOSTAT. 2014. Available online: http://faostat.fao.org/ (accessed on 13 May 2014).
24. Hurni, H. *Agroecological Belts of Ethiopia. Explanatory Notes on Three Maps at a Scale of 1:1,000,000*; University of Bern: Bern, Switzerland, 1998.
25. CSA. *National Land Utilizations, Crop Production and Livestock Survey Report*; National Statistical Agency of Ethiopia (CSA), 2012. Available online: http://www.csa.gov.et/ (accessed on 11 May 2014).
26. UN. *World Urban and Rural Population*; Population Estimates and Projection Section, United Nations Population Division: New York, NY, USA, 2014.
27. Demirbas, K.; Sahin-Demirbas, K.A. Compacting of Biomass for Energy Densification. *Energy Sources Part A Recovery Util. Environ. Eff.* **2009**, *31*, 1063–1068.
28. Tucho, G.T.; Weesie, P.D.; Nonhebel, S. Assessment of renewable energy resources potential for large scale and standalone applications in Ethiopia. *Renew. Sustain. Energy Rev.* **2014**, *40*, 422–431.
29. Barnes, D.F.; Floor, W.M. Rura enery in developing countries: A Challenge for Economic Development. *Annu. Rev. Energy Environ.* **1996**, *21*, 497–530.
30. Kowsari, R.; Zerriffi, H. Three dimensional energy profile: A conceptual framework for assessing household energy use. *Energy Policy* **2011**, *39*, 7505–7517.
31. Ameha, A. *Sustainable Supply of Wood Resources from Adaba-Dodola Forest Priority Area. Paper Presented on the Alumni Seminar*; Addis Ababa University: Addis Ababa, Ethiopia, 2002.
32. Bewket, W. Household level tree planting and its implications for environmental management in the northwestern highlands of Ethiopia: A case study in the Chemoga watershed, Blue Nile basin. *Land Degrad. Dev.* **2003**, *14*, 377–388.
33. O'Sullivan, K.; Barnes, D.F. *Energy Policies and Multitopic Household Surveys: Guidelines for Questionnaire Design in Living Standards Measurement Studies*; World Bank Publications: Washington, DC, USA, 2007.
34. Rosillo-Calle, F. *The Biomass Assessment Handbook: Bioenergy for a Sustainable Environment*; Earthscan: London, UK, 2007.
35. Jekayinfa, S.; Scholz, V. Potential availability of energetically usable crop residues in Nigeria. *Energy Sources Part A* **2009**, *31*, 687–697.
36. Zeng, X.; Ma, Y.; Ma, L. Utilization of straw in biomass energy in China. *Renew. Sustain. Energy Rev.* **2007**, *11*, 976–987.
37. Purohit, P.; Tripathi, A.K.; Kandpal, T.C. Energetics of coal substitution by briquettes of agricultural residues. *Energy* **2006**, *31*, 1321–1331.
38. Demirbas, A. Sustainable charcoal production and charcoal briquetting. *Energy Sources Part A* **2009**, *31*, 1694–1699.

39. Zinoviev, S.; Müller-Langer, F.; Das, P.; Bertero, N.; Fornasiero, P.; Kaltschmitt, M.; Centi, G.; Miertus, S. Next-generation biofuels: Survey of emerging technologies and sustainability issues. *ChemSusChem* **2010**, *3*, 1106–1133.
40. Weiland, P. Biogas production: Current state and perspectives. *Appl. Microbiol. Biotechnol.* **2010**, *85*, 849–860.
41. Batzias, F.A.; Sidiras, D.K.; Spyrou, E.K. Evaluating livestock manures for biogas production: A GIS based method. *Renew. Energy* **2005**, *30*, 1161–1176.
42. Bond, T.; Templeton, M.R. History and future of domestic biogas plants in the developing world. *Energy Sustain. Dev.* **2011**, *15*, 347–354.
43. Jingura, R.M.; Matengaifa, R. Optimization of biogas production by anaerobic digestion for sustainable energy development in Zimbabwe. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1116–1120.
44. Omer, A.; Fadalla, Y. Biogas energy technology in Sudan. *Renew. Energy* **2003**, *28*, 499–507.
45. Deublein, D.; Steinhauser, A. *Biogas from Waste and Renewable Resources: An Introduction*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
46. Lehtomäki, A. *Biogas Production from Energy Crops and Crop Residues*; University of Jyväskylä: Jyväskylä, Finland, 2006.
47. Rajendran, K.; Aslanzadeh, S.; Taherzadeh, M.J. Household biogas digesters—A review. *Energies* **2012**, *5*, 2911–2942.
48. Karaj, S.; Rehl, T.; Leis, H.; Müller, J. Analysis of biomass residues potential for electrical energy generation in Albania. *Renew. Sustain. Energy Rev.* **2010**, *14*, 493–499.
49. Scarlat, N.; Martinov, M.; Dallemand, J.-F. Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. *Waste Manag.* **2010**, *30*, 1889–1897.
50. Lal, R. Soil carbon sequestration impacts on global climate change and food security. *Science* **2004**, *304*, 1623–1627.
51. Haileslassie, A.; Priess, J.; Veldkamp, E.; Teketay, D.; Lesschen, J.P. Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agric. Ecosyst. Environ.* **2005**, *108*, 1–16.
52. Haileslassie, A.; Priess, J.A.; Veldkamp, E.; Lesschen, J.P. Smallholders' soil fertility management in the Central Highlands of Ethiopia: Implications for nutrient stocks, balances and sustainability of agroecosystems. *Nutr. Cycl. Agroecosyst.* **2006**, *75*, 135–146.
53. Duguma, L.A.; Minang, P.A.; Freeman, O.E.; Hager, H. System wide impacts of fuel usage patterns in the Ethiopian highlands: Potentials for breaking the negative reinforcing feedback cycles. *Energy Sustain. Dev.* **2014**, *20*, 77–85.
54. Valbuena, D.; Erenstein, O.; Tui, S.; Abdoulaye, T.; Claessens, L.; Duncan, A.J.; Gerard, B.; Rufino, M.C.; Teufel, N.; van Rooyen, A.; *et al*. Conservation agriculture in mixed crop-livestock systems: Scoping crop residue trade-offs in sub-Saharan Africa and South Asia. *Field Crops Res.* **2012**, *132*, 175–184.
55. Mengistu, M.G.; Simane, B.; Eshete, G.; Workneh, T.S. A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia. *Renew. Sustain. Energy Rev.* **2015**, *48*, 306–316.

56. Gwavuya, S.G.; Abele, S.; Barfuss, I.; Zeller, M.; Müller, J. Household energy economics in rural Ethiopia: A cost-benefit analysis of biogas energy. *Renew. Energy* **2012**, *48*, 202–209.
57. Fischer, G.; Schrattenholzer, L. Global bioenergy potentials through 2050. *Biomass Bioenergy* **2001**, *20*, 151–159.
58. Berndes, G.; Hoogwijk, M.; van den Broek, R. The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass Bioenergy* **2003**, *25*, 1–28.