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Biomass sources for a sustainable energy supply in Ghana – A case study for Sunyani

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ABSTRACT

A stable and affordable energy supply is the indispensable basis for the successful development of countries in West Africa. Ghana currently suffers from an energy crisis. The country is no longer able to meet the rising demand for electricity. At the same time, the energy supply needs to be switched to renewables to protect the climate and increase local added value. Therefore, local biomass utilization is crucial for the future Ghanaian Energy Mix. In this case study for Sunyani, suitable biomass residue sources were identified. The residues are divided into forest biomass, namely logging and sawmill residues from production zones of a forest reserve and residues from *Tetrapleura tetraptera* and food waste, consisting of residues from *Manihot esculenta* (cassava), *Musa × paradisiaca* (plantain) and kitchen waste. Abundance and energetic potentials were calculated and the feedstocks were characterized (elemental analysis, moisture content, ash content, calorific value, ash melt behavior and crude fat content). Sawdust from logging and sawmill residues, remaining from a specific harvested forest area, have an average abundance of 3.18 t/ha and 1.97 t/ha, respectively. This sawdust can be pressed to pellets and converted to 3.4 MWh_{el}/ha in a wood gasifier system. The average theoretical biogas yield from food waste and cassava/plantain peel residues is 823 l/kg with an average methane share of 48.6 vol%. A design of an integrated sustainable energy system consisting of a solar thermal dryer, a biogas plant, a wood gasifier and an absorption cooling machine, was proposed for electricity, heat, cold and cooking gas production in Sunyani. The study showed that utilizing biomass in Ghana in a modern and efficient way is applicable to solve energy problems, affect local markets positively and support the implementation of renewable energies in Ghana.

1. Introduction

1.1. Background and problem statement

The Republic of Ghana located along the Gulf of Guinea and the Atlantic Ocean is a state in sub-Saharan West Africa. It is bordered by the Ivory Coast in the west, Burkina Faso in the north and Togo in the east. The area with 238,000 km^2 is comparable with the UK. The tropical climate in Ghana is divided into the wet and the dry season. The wet seasons used to occur from April to July and from September to November with average annual rainfalls of 1100 mm in the north to 2100 mm in the southeast. Climate change already affected intensity and time of the rainfalls. The mean annual temperature has increased by 1 °C in the past four decades and the monthly rainfall and runoff has decreased by 20% and 30%, respectively, in the same period. A reduced precipitation and a 1–3 °C increase of the mean temperature by 2060 is predicted [1,2]. This will affect the agricultural sector, the coastal zones and the marine ecosystems, the energy production, the water resources and the daily lives of Ghanaians, dealing with lower crop yields and increasing food prices at the markets [2,3].

Ghana's forests are divided into two zones: the high forest zones in the southern region with closed forests and the savannah zone in the upper regions with open forest. There is a broad spectrum of types ranging from wet evergreen to semi-deciduous [4]. Ghana once was rich in forest resources but nowadays the resources are highly degraded due to wildfires, agricultural spread, illegal logging and illegal mining (galamsey).

One of the biggest challenges for developing countries is the effective and sustainable access to electricity for households and industry as this is indispensable for the improvement of people's living and working

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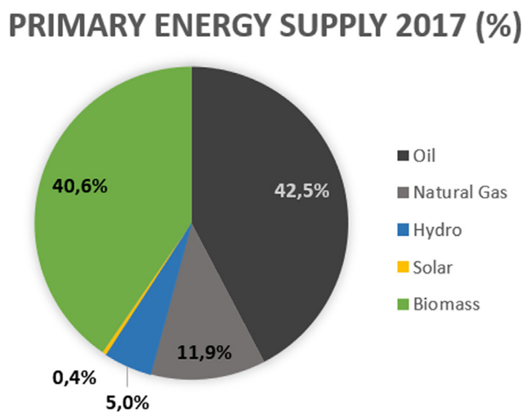

Fig. 1. shows the primary energy supply in the Ghanaian national energy mix in 2017 [12].

conditions. In Ghana, the national grid power access coverage in 2011 was 72%, while universal access to electricity with a 10% renewable share is the target for 2020 [5,6]. The electricity demand is significantly rising because of population growth, urbanization and expanding economy [6,7]. Obsolete transmission lines cause blackouts and approximately (app.) 4.1% transmission losses of total energy consumed [8,9]. Reduced and increasingly irregular rainfalls affect the efficiency of hydro power stations [10,11], which have a share of 39.9% in the power production mix of the country [8]. Despite the very high potential, photovoltaic and solar thermal systems have no considerable share in the power generation mix (0.2%), though recently Chinese investors supported the construction of a 20 MW photovoltaic plant. Thermal power production has a share of 59.9% in the national mix. While oil for power generation is almost entirely imported (even though, Ghana has national crude oil resources), the production of natural gas is used for local supply in Ghana. The primary energy supply is covered with oil and biomass, with shares of 42.5% and 40.6%, respectively, and small shares of natural gas and hydro, with shares of 11.9% and 5.0%, respectively [8,12]. The data is shown in Fig. 1.

Traditional cooking in rural areas makes biomass the most important renewable energy resource in the country. Nonetheless, it is rarely used for power production. Biomass conversion to electricity would reduce oil consumption and thus dependencies on oil imports and would also improve rural power supply. In 2017, the total biomass consumed was 32,900 GWh, which accounts for 40.6% of the total final energy consumed. 90–95% of this biomass is wood fuel and collected and burned in the traditional way [13].

The current share of installed electricity generation capacity from renewables (excluding large hydropower plants) in the national energy mix is less than 1% (0.4% in 2017) [8]. The total installed renewable electricity capacity (on-, off- and mini-grid) in 2017 was 42.7% [8]. The exact distribution is shown in Table 1 [8].

Ghana launched the "Ghana Sustainable Energy for All (SE4ALL) in May 2013, which, together with the Strategic National Energy Plan (SNEP), outlines the goals and pathways for improving the expansion of renewable energies. Ghana considers renewable energies as the key to a sustainable, affordable and independent energy supply in their energy supply mix [5,13]. The energy strategy of Ghana foresees an increase of at least 10% in renewable energy and modern biomass in the national generation mix by 2020. Furthermore, a reduction by at least 40% of the woodfuels used in the traditional way by 2020 [8]. Policies were recommended to the government in order to achieve these goals [14]. Additionally, the SNEP recommends to develop an energy market, which provides sufficient, viable and efficient energy services for Ghana in line with economic growth [15]. Therefore, the government of Ghana formulated its goal in the national energy policy "to make energy services universally accessible and readily available in an environmentally sustainable manner" [16].

Table 1
Installed renewable electricity capacity in kW.

Off-grid			On-grid			Mini-grid		Total
Solar	Wind	Dist. SPV	Utility Solar	W2E	Hydro	Solar	Wind	
7269	20	8530	22,500	100	4000	314	11	42,744

Dist. SPV: Distributed Solar PV; W2E: Waste-to-energy [8].

Regarding the needed acceleration of growth and thus the creation of jobs, Ghana aims to provide universal and efficient access to electricity by the year 2020 [5,17]. Renewable Energy has to be one important pillar of this electricity production, as the "Renewable Energy Act, 2011" pronounced the "provision for the development, management and utilization of renewable energy sources for the production of heat and power in an efficient and environmentally sustainable manner" [18]. The "Ghana National Climate Change Policy" (NCCP) was published in 2013 with the aim "to ensure a climate-resilient and climate-compatible economy while achieving sustainable development through equitable low-carbon economic growth for Ghana" [19].

As the government wants to meet the national energy goals by increasing the utilization of biomass for energy purposes, various studies have been conducted in this field. A broad overview of different biomass resources and biofuel production potentials in Ghana is provided by Duku et al. [7]. The resources include important energy crops, agricultural crop residues, forest product residues as well as urban and animal wastes. The data on the potentials of these resources mainly rely on statistics provided by the Food and Agricultural Organization (FAO) of the United Nations and the associated residues are calculated using residue-to-product ratios (RPR) or they emerged from older studies [7]. This study shows the immense potential of a variety of biomass resources in Ghana.

Kemausuor et al. [20] assessed the biomass residue availability and the bioenergy yields of different crop residues, animal manure, logging residues and municipal wastes. They state a technical potential of bioenergy from these sources in Ghana of 96 PJ in 2700 m^3 of biogas or 52 PJ in 2300 ML of cellulosic ethanol. In case of forestry residues in the form of slabs, wane, bark and sawdust, a total production of 0.35 MT/yr is reported, of which sawdust accounts for an amount of 0.081 MT/yr, which is a share of 23.2% of the total residues [20].

A wider investigation of the biomass potential of all sub-Saharan Africa is given by Dasappa 2011 [4]. The study estimates the potential power generation from agricultural and forestry residues at about 5000 MW and 10,000 MW by using 30% of agricultural and 10% of forestry residues. They also summarize some experiences in using biomass for gasification and highlight technological, economic and other key barriers for the implementation of the technique [4].

Mohammed et al. [21] gave an overview of agricultural biomass for decentralized rural energy in Ghana in 2012. Their investigations on the potentials were based on FAO statistics and on the literature of past studies. The potentials of wooden residues were not considered in the study. Different biomass conversion routes were shown, especially for the decentralized generation of electricity. The authors stated that "biomass is the foremost renewable energy source in Ghana", which is important to supply increasing rural energy demand. They concluded that deforestation can be reduced and negative environmental effects can be minimized by using other energy sources than wood fuel [21].

One important result of all viewed studies is that the biomass should be collected in a limited radius around the generating plant. Large distances to biomass collection areas and respective transport routes have to be avoided to avoid financial losses.

In the study by Derkyi et al. [23], the utilization of *Tetrapleura tetraptera* (local name: Prekese) waste in the form of charcoal for energy and climate change mitigation was investigated. Charcoal yield, physiochemical and energy properties were determined and the fruit was described as a very suitable alternative to wood for charcoal production [23].

The aim of this study is to investigate the potential of selected biomass residues in terms of quantities and conversion to electricity, to support the achievement of the Ghanaian goals in implementing renewable energies.

1.2. Forest biomass

Ghana's forests show a high diversity with the southern wet evergreen forests and the northern open semi-deciduous forests [4]. Ghana owned 5.52 million ha rainforest in 2006, which is one of the world's largest area [24]. The country's forest resources were reduced by wildfires, unsustainable logging and agricultural activity, illegal mining (known as "galamsey") [20,25,26] and migration to forest areas [7]. Therefore, timber harvesting was regulated by the Forestry Commission (FC), which implemented an "annual allowable cut" (AAC) of 2 million m^3 per year. The regulation of the ACC is executed by local communities, e.g. by chiefs and families. The ACC is only applied in the production zones, which are divided in compartments with areas between 100 and 150 ha [27]. These timber production zones are managed sustainably in a 40-year cutting cycle with defined diameter limits for cutting allowance for each timber species. Contractors can purchase harvest licenses from the Forestry Commission (FC) for specific compartments to harvest all marked trees. Motor manual harvesting with successive truck transportation to sawmills is the main allocation practice for material utilization (personal communication with FC expert). All trees from those compartments that are harvested and transported out of the forest are listed by the FC and provided the data base for the calculation of the logging residues in this study (Section 2.1). There are concerns that off-cuts are an important nutrition and fertilizer source for forest soils and therefore should not be totally removed.

The timber processing sector consists of large, medium and small-scale companies, with 30,000 small scale companies spread all over the country [28] and eight large companies, which are mainly located in Kumasi and share 80% of the export. The timber industry focuses on exporting primary and secondary timber products. Due to the unavailability of high technology processing machinery there is a lack of value added tertiary products [28].

The fuel wood consumption was 0.10 TOE/capita in 2017 [8]. App. 90% of the fuel wood is harvested in natural forests and only 10% are utilized wood wastes, e.g. logging and sawmill residues, and energy plantations [5]. This bioenergy is mainly used for household cooking in form of charcoal and firewood. For cultural reasons, women and girls suffer from inhaling the indoor fire emissions, which increases their incidence and mortality rate stronger than malaria [5,29]. Therefore, methods have to be developed to convert forest biomass to energy in a more efficient way [5].

Negative environmental impacts such as deforestation, global warming, acidification, eutrophication, smog and human toxicity, can be reduced by minimizing the wood waste of the timber and forestry sector through energetic utilization in modern and efficient biomass conversion systems [30]. The energetic use of wood waste can also contribute to an independent, sustainable and affordable energy supply in Ghana without felling more trees. There are large amounts of unused logging and sawmill residues generated by the timber industry [7,30–36], because of technological, organizational and management insufficiencies. The technological factors are obsolete and inefficient equipment while the organizational and management factors are inefficient process chains, administration, resource management and institutional maintenance [30,32].

Table 2 shows the state of the art of literature data on the abundance of sawmill waste based on different literature sources. Wood waste from the timber industry can be divided into two categories: solids (slabs, edgings, offcuts, veneer wastes and cores) and fines (sawdust, planer shavings and sander dust) [36]. Solids are mainly used as firewood and for charcoal production. Bush mills use solids to produce value-added products like local furniture or fencing. Sawdust is not yet used on large scale at all. A small share is occasionally burned in boilers on-site or used as feedstock for mushrooms [7,32,36,37].

The literature in Table 2 also shows the abundance of available logging residues, e.g. off-cuts from buttresses, branches, and crowns with foliage, which are left in the forest as they have no market value [3,7,21,22,30–32,34,38].

The fruit of the native and common deciduous tree *Tetrapleura tetraptera* (local name: Prekese), a tree on the fringe of the West African rainforest belt [39], is growing best in tropical climate in primary rain forests, but it can also be found in secondary forests. The four-winged fruit of the tree is used as spice, syrup, to cure hypertension and for beverages. The latter application yields the largest amounts of fruit residues, which are the two wooden wings. Derkyi et al. proposed the use of these wings for energy production [23].

1.3. Food and kitchen waste

Besides power supply coverage, food security is the main priority in developing countries, especially the avoiding of malnutrition caused by diets with unbalanced nutrient composition. As the competition between food and energy has to be avoided, the efficient and sustainable use of agricultural residues can contribute to a sustainable, intelligent and safe energy supply.

Food-to-fuel technologies can cause land conversion, deforestation, soil degradation and health problems [7,40,41]. However, there is a high abundance of agricultural waste in Ghana that has not yet been energetically utilized by efficient conversion technologies, as many studies have shown [4,5,7,15,17,19,21,22,31]. Most of this biomass represents an ideal feedstock for biogas plants. As this study is exclusively restricted to residues which are not consumable by humans, a deeper elaboration on the food-versus-energy issue was not carried out. It is assumed that utilizing these residues does not imply food energy conflicts, but rather contributes to solve these problems. Agricultural residues can be utilized locally in a modern and efficient way in order to achieve less dependency on fossil fuels and to develop new business models that create benefit for both local providers and energy producers.

Manihot esculenta, one of the oldest crops worldwide, is a woody perennial shrub with a starch rich root that provides food for an estimated 800 million people. It is resistant to drought, can be planted

Table 2
shows literature values on forest biomass residues in Ghana.

Publication	Reference Year	Sawmill residues [Mio m^3/a]	Sawmill residues [Mio t/a]	Sawdust[a] [Mio t]	Logging residues [Mio m^3/a]	Logging residues [Mio t/a]
[7]	2008	0.256	0.128	0.019	0.72	0.36
[30]	2000–2007	0.750	0.375	0.056	5.12	2.56
[36]	1986	0.271	0.136	0.020	–	–
[34]	1988	–	–	–	0.70	0.35

[a] calculated with a share of 15% of sawdust in the sawmill residues.

manually and is mainly grown by low-income farmers in isolated areas with poor soil qualities under unpredictable and low precipitation [42]. In Ghana, the starchy root is used for meals or to prepare flour and dough. The peels remain as a residue.

The fruit of the cooking banana plant *Musa × paradisiaca* is a banana-shaped fruit abundant in the daily diets of Ghanaians. It is similar in taste to potato and is a carbohydrate source, which is boiled, fried or baked. The ripe bananas turn from green to black, are peeled by hand in the kitchens and provide large quantities of residues [43].

Additional food waste is available in schools, canteens, restaurants and hotels every day and in large quantities. In comparison to the cassava and cooking banana waste it is preconcentrated and easier to collect. The food waste is either distributed to farmers and private households to feed dogs or cattle or it is dumped (personnel communication with restaurant owners). Food waste has high proportions of fats and carbohydrates, which makes it a good substrate for anaerobe digestion. Challenges in energetic utilization of food waste are storage and the respective hygienic precautions. Using these wastes requires both an infrastructure for collection and storage and a business model for a waste to energy supply chain.

1.4. Objective of this study

This study evaluates the biomass to power potential in Sunyani on the base of forest residues and food and kitchen waste. Available biomass in the Sunyani area is analyzed and the relation between quantities and energy outputs are elaborated. The design of an integrated sustainable energy system for the central Campus of the University of Energy and Natural Resources (UNER) is discussed.

2. Material and methods

2.1. Study area

The capital of the Brong-Ahafo Region in Ghana is Sunyani. Due to the road connection to Kumasi and a small airport, Sunyani became an important city and designated to a municipal district. Its population is given with app. 250,000 [45]. Surrounded by the southern Ashanti forests, Sunyani is a steadily growing city and home to the Brong-Ahafo regional government and high court. The two most important industries are the African Global Pharma Limited (AGP) and Newmont's gold, a mining company. The electric power distribution is provided by the Northern Electricity Department (NEDCo), a subsidiary of the Volta River Authority (VRA). They receive power at 34.5 kV from GridCo, which operates the transmission network at 161 kV and transform it to 11 kV for industrial customers and 440/230 V for residential usage [44].

2.2. Forest biomass potential calculation

Data acquisition, field trips and sample taking for this study were conducted at the University of Energy and Natural Resources (UENR) in Sunyani in summer 2017. Discussions with experts from the Forestry Commission were done to get information about the research area, the Asukese forest reserve in the moist semi-deciduous north-west. As this study focuses on the production zones in the forest only, it is assumed that the 40-year cutting cycle which is limited to defined diameters has no negative effects on the ecosystem of the forest areas because there is enough dead wood from storms or fires and other biomass like bark and foliage which provides enough nutrition and fertilizer for the soil. This assumption is based on interviews with officials of the Forestry Commission.

They further reported that it is important for them that the contractors take as much as possible of every tree out of the forest, because the residues present a fire hazard. This fact supports the decision for choosing logging residues as a suitable biomass source as they have a large potential for energy conversion.

This forest area is close to the university and will allow short transportation routes. Data from three currently harvested compartments in the Asukese forest reserve (No. 28A, 115 and 167, with areas of 79.32 ha, 147.61 ha and 137.12 ha, respectively) were chosen for the calculation of logging residues. In most cases, only the commercially exploitable part of the tree is taken during the harvest. This part is mostly limited to the logs of the stem for round-wood production and further value addition. Off-cuts from buttresses, branches and crowns with foliage are mostly left in the forest. The amount of these logging residues is estimated by calculations using allometric equations. The methodology and the equations used are shown in the following.

The data (stock surveys), provided by the FC in Sunyani, from the compartments 28A, 115 and 167 comprised the number and species of the harvested trees and classified each tree in seven diameter classes (diameter at breast height above 30–50 cm) [19]. The mean of each of the seven diameter classes was used for the allometric equations [46–48].

As the total tree height (H) was not available in the data of the stock surveys, two approaches with pantropical diameter-height allometric models were used. The first model for estimating tree heights was obtained from [49]:

$$\log_e(H) = \beta_0 + \beta_1 \log_e{}^*(D^*) + \varsigma 01^* A \tag{1}$$

The regional-classification-structure parameters β_0, β_1 and $\varsigma 01$ were 0.4619, 0.6362 and 0.0109, respectively [49]. The results were validated with the model from [48], which is an integrated pantropical diameter-height allometric model:

$$\ln(H) = 0.893 - E + 0,\ 760\ln(D) - 0.0340(\ln(D))^2 \tag{2}$$

where the bioclimatic stress variable E is defined as:

$$E = (0.178 \times TS - 0.938 \times CWD - 6.61 \times PS) \times 10^{-3} \tag{3}$$

with TS (temperature seasonality), CWD (climatic water deficit) and PS (precipitation seasonality). The stress variable E was obtained from the provided database [50].

Tree species specific densities were found in [46,51,52]. Mean values per species were calculated. Densities of related species were taken in case of a lack of data on listed species.

The results of four allometric equations were compared to estimate the above ground biomass (AGB)

$$(AGB)_{est} = 0.30^* d_{bh}^{(2.31)} \tag{4}$$

where AGB is aboveground biomass (kg) and d_{bh} is the diameter at breast height (cm) [46]

$$(AGB)_{est} = \rho^* \exp(-0.667 + 1.784\ln(d_{bh}) + 0.207(\ln(d_{bh}))^2 - 0.0281(\ln(d_{bh}))^3) \tag{5}$$

where ρ is density in (g/cm^3) and no tree height is considered [47]

$$(AGB)_{est} = 0.112^*(\rho^* d_{bh}{}^{2*} H)^{0.916} \tag{5'}$$

where H is the total tree height (m) [47]

and

$$(AGB)_{est} = \exp(-1.803 - 0.976E + 0.976\ln(\rho) + 2.673\ln(d_{bh}) - 0.0299(\ln(d_{bh}))^2) \tag{6}$$

where E is the bioclimatic stress variable for the location "Sunyani" (0.1820977) [48]

The mass of forest residues ($m_{res,f}$) was calculated by multiplying the AGB with the mean logging recovery rate factor ($f_{r,l}$) (Table 3).

The sawdust potentially obtained from the logging residues was calculated according to the equation:

$$m_{sd,f} = m_{res,f,m}{}^* f_{loss} \tag{7}$$

where $m_{sd,f}$ is the mass of the sawdust (t), $m_{res,f,m}$ residues in the forest

Table 3
shows the timber and residue share of the forest biomass in Ghana according to literature values.

Literature	$p_{t,f}$	$f_{r,l}$
[7][a]	0.25	0.75
[33][a]	0.50	0.50
[34][a]	0.52	0.48
[37][a]	0.45–0.55	0.45–0.55
[46][b]	0.30	0.69
Mean	0.42	0.57

$p_{t,f}$: logging residue share.
$f_{r,l}$: logging recovery rate factor.
[a] experimental values.
[b] allometric calculation.

Table 4
shows the literature values of sawmill residue recovery in Ghana.

Publication	$f_{r,s}$	$f_{sd,w}$
[32]	0.42	0.10
[7]	0.33	0.21
[36]	0.43	0.21
[37]	0.30–0.45	0.25
[35]	0.4–0.45	0.1
Mean	0.42	0.16

$f_{r,s}$: sawmill recovery rate factor (all residues, incl. e.g. side boards, wood chips etc.).
$f_{sd,w}$: share of sawdust within the sawmill recovery.

and f_{loss} the transportation losses (0.75).

The sawdust obtained from the log processing in sawmills was calculated according to Eqs. 8 and 9 with the factors from Table 4 under the assumption of a complete utilization of the harvested timber in Ghana's saw mills. This assumption is based on the log export ban policies in Ghana and the high priority on exporting value added secondary and tertiary wood products [38].

$$m_{logs,harv} = AGB_n - m_{res,f,m} \quad (8)$$

$$m_{sd,s} = m_{logs,harv} * f_{r,s} * f_{sd,w} \quad (9)$$

The last step was to calculate the amounts of pellets which can be produced from the sawdust. By pelletizing residues the bulk density can be minimized and the energetic density can be maximized [53]. The gasification process requires larger particle sizes than sawdust for an optimum energy conversion. The total quantity of pellets $m_{p,\ total}$ (t) that can be produced from the sawdust was calculated with the conversion factor of 1.7 t wet sawdust to 1 t pellets [54].

2.3. Forest biomass laboratory analysis

Two sawmills in Kumasi and Sunyani were visited and fresh sawdust samples (SD1, SD2) from the tree species *Triplochiton scleroxylon* and *Celtis* spp. were taken from a typical small-scale sawmill. *Triplochiton scleroxylon* and *Celtis* spp. are one of the most used and processed species for all primary products and for kiln dried secondary products in Ghana and thus have a representative character and it can be assumed that a large proportion of the sawdust in the sawmills contain this species [28]. The samples were dried, the moisture content was determined, and they were shipped in air tight containers to the laboratory of the University of applied forest sciences Rottenburg (HFR), Germany.

The *T. tetraptera* fruits (TR) were provided by a local farmer in Sunyani. The two fleshy wings were removed and the two wooden wings were shipped to the laboratory of the HFR.

The sawdust samples (SD1, SD2) were sieved (0.25 mm) and the *T. tetraptera* residues (TR) were grinded in a cutting mill (0.25 mm, pulverisette 19, Fritsch GmbH, Markt Einersheim, Germany). Moisture content (MC), ash content (AC), calorific value (CV) and elemental analysis (CHNS-determination) as well as the ash melting behavior (AMB) were determined according to the specific DIN standard (Table 5) [55–59].

2.4. Energy from forest biomass

The specific wood fuel consumption data of a reference biomass CHP system (HKA 45, Spanner Re^2 GmbH, Neufahrn, Germany, fixed-bed wood gasifier with combined heat and power plant, Table 6) was used to calculate electricity and heat output from conversion in a wood gasifier [60]. For the calculations, the determined amounts of pellets that could theoretically be produced out of the calculated sawdust potential in this study (Table 10), were assumed. Further it was assumed that the considered pellets meet the requirements of the DIN EN ISO 17255–2 and that the gasifier runs under optimum conditions.

2.5. Food and kitchen waste potential calculation

Because of limited capacities in this study it was decided to select two types of agricultural waste. The waste from food processing kitchens in hotels, schools, canteens, restaurants and chop bars were studied more closely. It was found that peelings and leftovers from *Manihot esculenta* (cassava) and *Musa×paradisiaca* (plantain) are available in large quantities in all kitchens. The data on kitchen leftovers and waste from cassava and plantain peels was obtained by using Ghana's harvest volume in 2016 [61]. The residue-to-product ratios (RPR) for cassava and plantain peels were 0.25 and 0.5, respectively [20]. Further information on food waste management was obtained from discussions with local farmers and kitchen managers.

2.6. Food and kitchen waste laboratory analysis

Hotels, restaurants and large kitchens in the Sunyani municipality were interviewed and dump sites were visited. Availability and transport issues were assessed and cassava (CP) and plantain peels (PP) were collected both in a restaurant (CP1, PP1) and a fufu chop bar (CP2, PP2). The peels were taken from different heights in the disposal sacks and were shipped to the laboratory of the HFR. Food waste samples

Table 5
shows the parameters, abbreviations (abr.), standards and units of the laboratory analysis for both forest biomass and food waste.

Parameter	Abr.	Norm	Unit
Moisture content	MC	DIN EN 14774–2:2009	wt%
Ash content	AC	DIN EN 14775:2009	wt%
Calorific values	CV	DIN EN 14918:2009	J/g d.b.
Carbon, hydrogen, nitrogen and sulfur contents	CHNS-determination	DIN EN ISO 16948:2015	wt% d.b.
Ash melting behavior	AMB	DIN CEN/TS 15370–1:2006	°C
Crude fat and[a] total fat content		DIN EN ISO 11085:2015	% d.b.

wt%: weight %; d.b.: dry basis; oDM: organic dry matter; SST: shrinking starting temperature; DT: deformation temperature.
[a] only food waste.

Table 6
lists the technical data of the Spanner gasifier HKA 45.

Electrical Power	45 kW_{el}, efficiency 23.3%
Heat Power	102.2 kW_{th}, efficiency 56.1%
Wood fuel quality	Natural wood in form of pellets, wood chips or Ø3cm briquettes Max. water content < 13% Max. fines (< 4 mm grain size) 30%
Wood fuel consumption[a]	0.9 kg/kWh_{el}
Outlet temperature	85 °C
Return temperature	65 °C

[a] Depending on the quality of the wood chips. Technical data: 05/2017 [60].

were obtained from the cafeteria of the UENR (FW1), a fufu chop bar (FW2) and a restaurant (FW3). The food waste contained beans, plantain, fufu (cassava), banku (maize), rice, soup, fish, meat, bones, stew, noodles, and chicken. Each sample was homogenized and then transported.

All food waste samples were grinded with a cutting mill (1 mm, pulverisette 19, Fritsch GmbH, Markt Einersheim, Germany). The analyses listed in Table 5 were applied. The crude fat and total fat content was determined according to corresponding standards [62]. Crude protein, crude fiber content and the nitrogen-free extracts (NFEs) were calculated by multiplying the nitrogen content of the samples with the factor 6.25 [63]. The amount of carbohydrates was calculated as the difference of the sum of ash-, crude fat-, and protein content and the total organic content.

2.7. Biogas potential calculation

The theoretical biochemical methane potential (BMP_{Th}) of the cassava and plantain peels and food residues was calculated with the stoichiometric approach according to Boyle [64] and the substrate specific approach according to Baserga [65]. The presence of proteins required the stoichiometric calculation of ammonia H_2S by Boyle's equation [63,66]:

$$\frac{Mol}{gas}[mol] \rightarrow \left(\frac{a}{2}+\frac{b}{8}-\frac{c}{4}+\frac{3\times d}{8}+\frac{e}{4}\right)=CH_4$$
$$\left(\frac{a}{2}+\frac{b}{8}-\frac{c}{4}+\frac{3\times d}{8}+\frac{e}{4}\right)=CO_2$$
$$d=NH_3;\ e=H_2S \tag{10}$$

where a, b, c, d, and e are the molar quantities of the elements C, H, O, N and S, respectively.

Derived from (10) the theoretical methane yield in l/kg DM (dry mass) was calculated by relating the molar mass of CH_4 to its density at 0 °C ($\rho_{0\,°C}$ = 0.000716 g/cm³). The methane share in the biogas was calculated by relating the theoretical methane yield to the sum of all gas yields that were calculated with the respective specific densities (CO_2: 0.00196 g/cm³, NH_3: 0.00076 g/cm³, H_2: 0.00154 g/cm³).

The substrate specific yield was calculated with the values of the "Weender Futtermittelanalyse" [63] (Table 7) and then multiplied with the specific biogas yields:

$$BMP_{th,\ Baserga}=x_{carb}\times q_{carb}+x_{prot}\times q_{prot}+x_{fat}\times q_{fat} \tag{11}$$

where $BMP_{th,Baserga}$ is the theoretical gas yield (l/kg oDM), x is the substance quantity (carbohydrates, proteins, fats) (g/kg oDM) and q is the specific biogas yield according to Table 7 (l/kg OS).

The share of methane in the biogas was calculated with the weighted mean of the substrate shares given in Table 7.

Table 7
shows the substrate specific biogas yields with their respective CH_4 share.

Substrate	Biogas yield [l/kg OS]	CH_4-content [vol%]
Carbohydrates	790	50
Crude proteins	700	71
Crude fats	1250	68

according to Baserga [66].

Table 8
shows the energy content of methane and biogas and the conversion efficiencies for CHPs.

Reference	Unit	Value
1 m³ methane	kWh	9.97
CHP $efficiency_{el.}$	%	28–47
CHP $efficiency_{th.}$	%	34–55
CHP $efficiency_{total}$	%	85–90

[68].

2.8. Conversion of biogas to electricity

The conversion factors for electricity and heat of gas otto engines are listed in Table 8 [67]. The mean was considered for the electrical and thermal output calculation.

The conversion of the methane content to power was calculated by multiplying the average food waste per capita in Ghana (110 kg/a, [68], the population in Sunyani (250,000 in 2012 [45] and a 30% electrical conversion efficiency.

3. Results

3.1. Forest biomass potential results

The comparative results of the AGB were calculated with the four different allometric equations and are displayed in Table 9. The different models yield *AGB* estimations with a high variation for each compartment. The variation coefficient was 41%, 35%, and 35% for the compartments 28, 115, and 167, respectively. Table 10 shows the respective residue sawdust from these compartments and the sawdust from the log processing in the sawmills. All values are added to a total amount of sawdust. The variation coefficient of the pellet production per ha for the three different compartments (Table 10) was 28%.

3.2. Forest biomass laboratory analysis results

Table 11 shows the results of the forest biomass analysis. *Tetraptera tetrapleura* shows high nitrogen and sulfur content (55% and 33%, respectively) and low moisture and ash contents in comparison to the tree species *Triplochiton scleroxylon* and *Celtis* spp. The calorific value is higher, while the shrinking temperature of *T. tetrapleura* is much lower than the shrinking value of the tree species (Table 11). The ash deformation temperatures are species unspecific in this study.

3.3. Forest biomass energy conversion potential

Table 12 shows the energy output of the pellets (Table 10) calculated with the given technical specifications of the Spanner Re² GmbH CHP system HKA 45 (Table 6). Residues from one compartment can be converted to 319–385 t of pellets, which equals a power output of 345–428 MWh_{el} and a thermal energy output of about 815–983 MWh_{therm}.

3.4. Food and kitchen waste potential results

Table 13 shows production [61] and residue potentials [20] of cassava and plantain in Ghana for 2016. Analysis of the available data for the last 50 years showed that the production rates steadily increased [61].

Table 9
shows the results of the calculated *AGB* per compartment and allometric equation.

(AGB) [t]						Residues [t]	Spec. mean [t/ha]
Comp. No.	Henry et al. [46]	Chave et al. [47]	Chave et al. [47]	Chave et al. [48]	Mean	$m_{res,f,m}$	$m_{res,f,spec}$
28	3815	1400	4812	2449	3692	1384	17
115	5757	2091	3557	3617	4310	1616	11
167	4797	1783	2934	2987	3572	1340	10

$m_{res,f,m}$: mean of total mass of residues left in the forest, $m_{res,f,spec}$: specific mean related to the area of the compartment.

3.5. Food and kitchen waste laboratory analysis results

Table 14 shows the results of the laboratory analysis. The food residues show the highest nitrogen and sulfur content ($\bar{x} = 3.19$ wt%o.d.b. and 0.4 wt%o.d.b., respectively) and have the highest crude fat and protein content ($\bar{x} = 18.26$ wt%o.d.b. and 19.96 wt%o.d.b., respectively) in comparison to cassava peels and plantain peels ($\bar{x} = 0.95$ wt% o.d.b. and 0.152 wt%o.d.b. for nitrogen and sulfur, respectively, and 2.7 wt%o.d.b. and 5.97 wt%o.d.b. for crude fat and protein, respectively). The moisture and ash content are high for all samples ($\bar{x} = 77.02$ wt% and 8.88 wt%o.d.b., respectively).

3.6. Biogas potential and conversion to electricity

Table 15 presents the theoretical biogas yield according to the stoichiometric Boyle and the substrate based Baserga approach. The stoichiometric approach (BMP_{Th} Boyle) yields higher BMPThs for the food residues in comparison to the substrate specific approach (BMP_{Th} Baserga), but slightly lower methane contents for the food waste.

The estimated methane potential from anaerobe digestion in Sunyani is app. 11 billion L, which is 7.876 billion kg, which equals to 33 billion kWh electrical power per year.

4. Discussion

4.1. Discussion on forest biomass

The allometric model of Chave et al. [47] showed a much lower AGB because it does not consider the tree heights (Table 9). Therefore, the result of this allometric equation was not considered in the mean value (Table 9). The impact of the tree heights on the allometric results indicate their necessity for a correct forest inventory in the Asukese Forest Reserve. In general, the allometric equations do not substitute a field forest inventory.

Mineral nutrients are not evenly distributed within the different parts of a tree but concentrated in the residual biomass, mainly in the crown and leaves. From an ecological point of view the removal of these assortments can have a negative impact on the stability of the ecosystem, which depends on the nutrient concentration in the soil. Soil degradation, especially acidification due to intense forest utilization, has an impact on the timber yield, as well. Such effects are not to be expected in the Asukese Forest Reserve, as a 40-year cutting cycle is kept, low diameter trees, bark and foliage are not removed and storms and fires induce a high share of decomposing deadwood (personal communication with officials from the Forestry Commission). The potential removal of logging residues will reduce the fuel load on the forest floor, which in turn will prevent crown fires.

Table 11
shows the results of the laboratory analysis for the forest biomass samples.

Parameter	*Tetrapleura tetraptera* sawdust	*Triplochiton scleroxylon* sawdust	*Celtis* spp. sawdust	Unit
C	46.51	46.19	46.09	wt% d.b.
H	6.26	6.31	6.43	wt% d.b.
N	0.73	0.44	0.50	wt% d.b.
S	0.32	0.25	0.23	wt% d.b.
Moisture Content	9.44	50.96	38.08	wt%
Ash Content	2.42	3.24	3.06	wt% d.b.
Gross Calorific Value q_{gr}	19.4	18.4	18.4	kJ/g d.b.
Net Calorific Value q_{net}	18.1	17.1	17.2	kJ/g d.b.
ST	743	1096	1204	°C
DT	1370	1355	1299	°C

wt%: weight %; d.b.: dry basis; oDM: organic dry matter; ST: shrinking temperature; DT: deformation temperature.

Further positive aspects of the residue utilization are a decreasing deforestation rate by satisfying the increasing energy demand in Ghana [3,5,17,26,30,32]. The officials of the Forestry Commission already motivate contractors to utilize residue biomass.

The high species variation in Ghana's timber industry is a challenge for pelletization due to a variation of the wood density, extractive content and mineral content. Though many biogenic feedstock can be pressed to pellets, the homogeneity of the raw material is important to produce pellets with constant quality [53]. This constant quality (e.g. density, moisture content, share of fines) is necessary to guarantee a stable gasification process with low maintenance and high power output. The higher the variation of the pellet quality, the higher will be the deviation from the power estimations given in Table 12. Sawmills, which are specialized on processing selected tree species, are a preferable feedstock source. Pelletizing sawdust for energetic utilization will have a high environmental impact, as it is common practice to burn the sawdust over the weekends (personal communication with sawmill

Table 10
shows the conversion of the forest biomass to pellets per compartment and per ha with a densification factor 1.7.

Comp. No.	$m_{logs,harv}$[t]	$m_{res,\text{logs}}$[t]	$m_{sd,f}$ [t]	$m_{sd,s}$ [t]	$m_{sd,f,spec}$[t/ha]	$m_{sd,s,spec}$[t/ha]	$m_{p,sd,s}$[t]	$m_{p,sd,f}$[t]	$m_{p,total}$ [t]	$m_{p,spec}$ [t/ha]
28	2307	1338	346	214	4.36	2.70	126	204	330	4.2
115	2694	1562	404	250	2.74	1.69	147	238	385	2.6
167	2233	1295	335	207	2.44	1.51	122	197	319	2.3
Total	7234	4195	1085	671	**3.18**[a]	**1.97**[a]	395	638	1034	3.0[a]

$m_{logs,harv}$: harvested logs, $m_{res,\text{logs}}$: residues from log processing in the sawmill, $m_{sd,f}$: sawdust from milled forest residues, $m_{sd,s}$: sawdust from log processing residues. $m_{sd,f,spec}$: sawdust from milled forest residues per ha, $m_{sd,s,spec}$: sawdust from log processing residues per ha, $m_{p,\ sd}$: mass of pellets produced from respective sawdust, $m_{p,spec}$: pellets.

[a] mean.

Table 12
shows the pellet amounts per forest compartment and the respective theoretical energy outputs.

Comp. No.	$m_{p,\ sd,s}$ [t]	$m_{p,sd,f}$ [t]	$m_{p,total}$ [t]	$W_{el,total}$ [MWh]	$W_{th,total}$ [MWh]	$W_{el,per\ ha}$ [MWh]	$W_{th,per\ ha}$ [MWh]
28	126	204	330	366	842	4.6	10.6
115	147	238	385	428	983	2.9	6.7
167	122	197	319	354	815	2.6	5.9
Total	395	638	1034	1691	2640	**3.4**[a]	**7.7**[a]

$m_{p,sd,s}$: pellets from sawmill sawdust, $m_{p,sd,f}$ pellets from forest residues, $m_{p,total}$: total amount of pellets (sawmill + forest residues), W_{el}: electrical energy, W_{th}: thermal output.
[a] mean

Table 13
shows the data on production and residues of cassava and plantain peels in Ghana in 2016 [61].

	Production [Mt/a]	Residues [Mt/a]
Cassava	17,790	4450
Plantain	3950	1976

workers). The utilization of sawmill residues, e.g. shavings and reject boards, will reduce the waste disposal costs, as well [37].

The moisture content of Celtis spp. and Triplochiton scleroxylon, with 38.08% and 50.96% respectively, was measured after the sawing of the logs and represents the fresh water content. However, the high moisture contents of Celtis spp. and Triplochiton scleroxylon will require drying before storage and pelletization. Moisture contents above 20% induce fungal and bacterial growth [69]. 10–12% moisture content is the optimum for pelletization [53]. The sawmills can arrange pre-drying of their sawdust (personal communication with sawmill manager). The pellet mill should be close to the sawmill and work under one organizational roof or even have the same owner. This will ensure short transportation and an effective organization. It can be a feasible strategy for future gasification applications as well to focus on one source of sawdust for pelletization, e.g. Tetrapleura tetraptera sawdust. This biomass has a comparably low ash and moisture content and a high heating value in comparison to the other biomass (Table 11), which makes it a potential gasification fuel (Table 6). The ash content of alternative fuels, e.g. oak acorns, coconut palm stems, eucalyptus and wheat grains is higher than the ash content of T. tetraptera [70]. Ash contents in the literature range from 0.3% to 3% in temperate zones to a maximum of 5% in tropic areas [53,70–73]. Adegoke et al. found a 3.75% ash content for residues from Triplochiton scleroxylon, which is comparable to our result [74]. All ash content values exceed the standard, but the deformation temperature of the ash is above the temperature in a fixed bed gasification. However, practical experiments with small scale gasifiers have to prove the feasibility of T. tetraptera. The high ash content can cause particulate matter emissions and filter clogging, as well as slag formation. This shortens the maintenance intervals and will lead to lower efficiency and sustainability. The calorific value of all three investigated forest biomass is in the lower range of wood (17.1 J/g–20.6 J/g) [75]. Net calorific values for Triplochiton scleroxylon are given with 15.3 J/g [76] and 14.65 J/g [77]. 16 J/g is an average species unspecific value for sawmill sawdust in Ghana [31].

Nitrogen concentrations in Celtis spp. and T. scleroxylon are higher (0.5% and 0.44%, Table 11) in comparison to European species, e.g. spruce, beech and fir (0.1%, 0.22% and 0.17%, respectively) [74,78]. European species usually have a low sulfur content (< 0.1%) [74,79,80], but the sulfur content of Celtis spp. and Triplochiton scleroxylon shows comparably high values (0.23% and 0.25%, respectively, Table 11). The higher sulfur and nitrogen content of T. tetraptera will cause higher SOx and NOx emissions in comparison to the two analyzed tree species (Table 11). All N and S values exceed the maximum levels given in the European pellet standard (DIN EN ISO 17255-2). Further research must focus on lignin and extractives contents, pelletization of the sawdust as well as particle and gaseous emission analysis of these fuels. C- and H- concentrations of hardwood species range between 41.9% and 51.6% and 5.56–8.32%, respectively [73,79,80]. Both wood species and the T. tetraptera sawdust show values in the middle of this range (Table 11).

4.2. Discussion on food and kitchen waste

The cassava and plantain residues in the Sunyani area can only be estimated in the course of this study. Local farmers said that the harvested amount was very low at the time of the conducted field trip due to drought. The market prices for cassava and plantain were three times higher than average. The Statistic, Research and Information Directorate (SRID) report informed that the Brong-Ahafo Region is the second largest cassava producer in Ghana [81]. The average yields of cassava and plantain under a sufficient precipitation regime are 18.3 and 10.8 Mt/ha, respectively. If "more effective extension and use of recommended technologies" will occur, the potential yields will be 48.7 and 20.0 Mt/ha, respectively [81]. Further area-specific studies must be carried out in order to evaluate the concise potential of these biowaste products.

Staff and owner of small kitchens in Sunyani reported that the biological leftovers are often fed to dogs and cattle and that it is possible that no large amounts of food waste are left for biogas production.

Table 14
lists the results of the food residue characterization of agriculture and food residues from the laboratory analysis.

Parameter [wt%]	Cassava Peels CP1	Cassava Peels CP2	Plantain Peels PP1	Plantain Peels PP2	Food Residues FR1	Food Residues FR2	Food Residues FR3
C	37.10	42.25	38.36	40.96	47.78	44.66	46.05
H	6.13	6.82	6.40	6.47	8.04	7.16	7.45
N	0.63	1.40	0.75	1.04	3.42	2.79	3.37
S	0.17	0.15	0.16	0.13	0.33	0.41	0.47
O	55.97	49.39	54.34	51.40	40.43	44.98	42.66
Moisture Content	70.84	73.59	82.50	85.58	68.44	77.22	80.94
Ash Content	8.32	5.78	9.00	10.76	9.91	9.86	8.53
Crude Fat Content	1.53	1.53	3.88	3.88	18.26	18.26	18.26
Crude Protein Content	3.94	8.74	4.68	6.52	21.39	17.44	21.06
Crude Fibers and NFE	86.22	83.95	82.44	78.83	50.45	54.44	52.15

wt%: dry weight %; NFE: nitrogen-free extract.

Table 15
shows the theoretical biogas yields of the food residues.

	Unit	Cassava Peels CP1	Cassava Peels CP2	Plantain Peels PP1	Plantain Peels PP2	Food Residues FR1	Food Residues FR2	Food Residues FR3	Mean ± SD (vc)
BMP_{Th} Boyle	l/kg DM	661	863	714	795	1156	1001	1076	895 ± 173(19)
Methane content	vol%	49.1	48.6	49.0	48.8	47.4	47.5	47.2	42.2 ± 0.76(2)
BMP_{Th} Baserga	l/kg DM	728	743	733	717	776	780	788	752 ± 27(3.5)
Methane content	vol%	51	53	52	53	60	59	60	55 ± 3.7(7)
Total mean BMP_{Th}	l/kg								**823**
Total mean Methane content	vol%								**48.6**

BMP_{Th}: theoretical biogas potential, DM: dry matter, SD: standard deviation, vc: variation coefficient.

Therefore, the focus of the food waste collection should be on large kitchens and canteens, e.g. in schools, universities, hotels and restaurants. The staff of these large kitchens expressed their willingness to collect the food waste separately in case there is an infrastructure to collect and utilize it. The separation of the waste is necessary to avoid critical substances, e.g. bones, egg shells and fibrous materials that inhibit the fermentation process. The process engineering and the plant operation have to be adapted to these materials, because they can obstruct stirring and discharging of the biogas reactor. Other promising sources were not analyzed in this study but can also give a contribution to a waste to energy system in Sunyani. Municipal solid waste (MSW) from dumping sites has a high organic content in developing countries [82,83], while coffee production residues can yield high gas amounts, as well.

The theoretical biogas and methane yields of cassava, plantain and food waste, calculated using two approaches, are given in Table 15. The stoichiometric and substrate specific approaches yield the theoretical maximum production, which will not be realized under field conditions.

The results of laboratory analysis of moisture contents of cassava and plantain peels are 72.2% and 84.04%, respectively. Ash contents were determined to be 7.05% and 9.88%, respectively. Compared to analyses in the literature, the values for cassava are in the range of previous studies that state moisture contents of 69.03–72.00% [84] and 66.08–72.36% [85]. The measured ash contents of cassava peels are significantly higher compared to literature values which are given with ranges of 1.28–4.05% [84] and 2.90–3.25% [85]. Determined ash contents of plantain peels are lower than the results from literature, which are in the range of 12.5–17.24% [86] and 14.3% [87]. Deviations in the ash contents from both cassava and plantain peels, can arise due to the degree of soiling which varies with intensity of cleaning the raw material before peeling. Moisture contents vary with air drying time and the form of storage e.g. in closed bags or on heaps.

Nitrogen in the substrate yields ammonia in the biogas reactor, which increases the pH. While the main problem of the anaerobe digestion is the acidification due to a too high substrate feeding rate, an increasing pH can harm the microbial community in the reactor. However, the nitrogen level in the kitchen and food waste (Table 14) is not as high as e.g. in chicken manure and, therefore, will most probably have no negative impact on the biogas production. The critical ammonia concentration is 3–5 g/L. Sulfur yields hydrogen sulfide, which inhibits microbial activity in the biogas reactor at a concentration above 30 mg/L. The relatively low levels of sulfur in the food waste will most probably not cause inhibition (Table 14). Future projects will implement a biogas plant in Sunyani in order to assess the efficiency of biogas production under local conditions. In case of microbial inhibition by NH3 or H2S the low-level N and S substrates cassava and plantain peels (Table 14) can be mixed with the food waste to reduce the relative N and S content in the substrate.

4.3. Design of an integrated sustainable energy system

The aim of this study was to locate suitable biomass waste in the Sunyani area and characterize it in terms of chemical composition, energetic yields and conversion properties. A concept for an integrated sustainable bioenergy system in Sunyani was generated. This bioenergy concept has to be widened in the future in order to reflect the whole production and supply chain from feedstock primary production, logistics, energy production and energy supply, including technical and economic efficiencies. An initial action will be the implementation of a research plant within a R&D project at the campus of the University of Energy and Natural Resources in Sunyani (UENR) in order to explore the technical feasibility of decentralized power production systems, run with local biogenic residues. Based on the preliminary calculations of this study, a first draft of the research facility was developed (Fig. 2).

The thermal off-energy of the gasifier/CHP can be converted to cool air by the proposed absorption chiller. 2,640MWhtherm (Table 12) can be converted to app. 1,848MWhcool that enables the chilling of app. 184,800 m2 living and working space (cooling efficiency 0.7 [88]). The estimated theoretical methane potential from anaerobe digestion in Sunyani is app. 12.4 billion L, which equals to 4.1 billion kWhel × a − 1. The conversion of the methane content to power was done under consideration of the average food waste per capita in Ghana (110 kg/a, [69]), the population in Sunyani (250,000 in 2012 [46]) and a 30% electrical conversion efficiency. The power generation yields app 8.2 billion kWhtherm × a − 1 (off-heat from CHP, 60% thermal efficiency), which can be converted to 5.74 billion kWhcool × a − 1 by absorption chilling (cooling efficiency 0.7 [88]). This allows the chilling of app. 0.3 mio m2 living and working space during the summer season, assuming that 100W chill 1 m2.

4.4. Forest biomass allocation

The sawmill sawdust has the highest transportation efficiency, as it is preconcentrated. Sawdust transportation is cheap in comparison to logging residue allocation. In Europe, the most efficient method to collect forest residue biomass is on-site chipping and transportation of the wet chips to CHPs by trailers. Many CHPs do not require pre-drying of the biomass but use moist fuel to reduce the oven temperature. Using moist biomass is no option for the proposed integrated renewable energy concept for Sunyani as it can neither be processed to pellets nor gasified directly. Therefore, either air drying in the forest or air/kiln drying at the pelletization site is recommended. Allocation of raw material can also be performed by subcontractors, but the more feasible biomass will be sawdust due to its availability. The transport chain for T. tetraptera cannot be estimated properly at present. It is probable that larger customers buy the fruits directly from the plantation and process it in a centralized facility. The waste would be preconcentrated in this case. If many small customers process the fruit for local markets, an efficient allocation will not be possible. Further field studies should focus on the allocation chain of T. tetraptera, as this lignocellulose source is a promising gasification fuel in comparison to the sawdust analyzed in this study (Table 11). The T. tetraptera fruits are already dry, but they have to be chipped. Experiments with the Spanner gasifier in the frame of the proposed R&D project will reveal the optimum particle size for this fuel. Sawdust has to be pelletized, as the gasifier cannot gasify sawdust. The fast kinetics of the small particle gasification

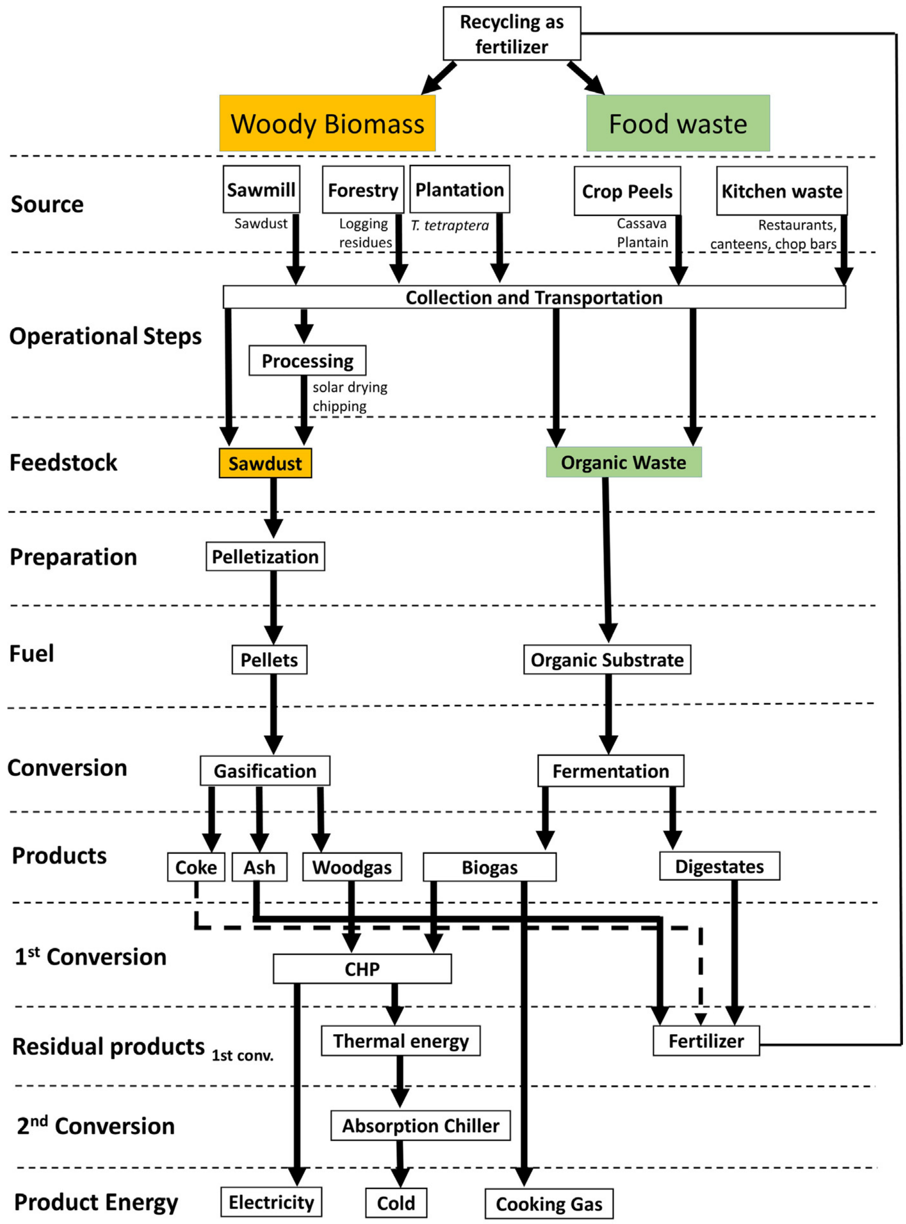

Fig. 2. Shows the potential design and flow chart of the integrated energy system from woody biomass and food waste at UENR campus in Sunyani. (not to be printed in color).

will shift the process to high temperature direct combustion and, therefore, only low calorific CO2 and H2O product gas would be produced. The off heat of the gasifier is the major product of the gasification process, as the electrical efficiency of small fixed bed gasifiers is low (Table 8). This off-heat can be valorized by the absorption chiller. Another residue of the gasification process will be the coke that accumulates in the tubing of the gasifier. This coke has to be removed during the maintenance intervals and the UENR provides trained personnel to ensure an efficient wood gas production. As the coke has a high organic content it can be used as a soil regeneration agent that improves plant growth.

4.5. Food waste allocation

Waste management in Ghana is either unorganized or not existing at all. The collection practiced in the Accra Metropolis and in Kumasi are house-to-house and communal collections. In smaller towns incinerators were built, but these facilities have no environmental impact assessment and negatively affect people's health [83]. A collection, separation and storage system for organic waste has to be developed and implemented in order to valorize this energy resource. Installing a collection system can offer benefits for the people and the environment by developing new business models and by implementing a retrieval and recycling system for organic waste. However, this cannot be achieved on short term. Therefore, the project will demonstrate an efficient and viable utilization of converting food waste into cooking gas on the base of pre-concentrated food waste in restaurants or large kitchens. The project will generate technical and economic data for the adaption of other food waste sources. The performed substrate analysis (Table 15) resulted in a relatively low variation of the overall gas yield. However, a precise analysis of the food waste composition of selected restaurants and kitchen, e.g. the university canteen, should be undertaken to verify these preliminary results.

According to positive experiences with small scale biogas plants for cooking gas production, e.g. in India or Nepal, a successful implementation of similar utilization paths can be expected. This will be accompanied by research concerning the entire added value chain efficiency. Biogas production parameters, e.g. stirring rate and substrate feed in rate, have to be adapted to the kitchen food waste. A medium scale approach will enable power generation but might suffer from substrate inhomogeneity. There are examples of medium scale biogas plants in Germany or Switzerland that constantly generate power from an agricultural residue substrate mix. The main obstacle in this case will probably be the lack of trained personnel that constantly cares for maintaining the digestion process. Training of personnel by experts is a crucial pillar for the biogas module of the "lighthouse project" to be implemented at the UENR campus.

5. Conclusions

Ghana's energy crisis requires solutions in order to pave the way for economic growth, affluence and life quality. Ghana is one of the most developed countries in Africa and can, by learning from the mistakes of developed western economies, shift to a sustainable industry. Bioenergy is a promising option to satisfy the growing energy demand and this paper outlines the potential in Sunyani for biogas and wood gas production by food and kitchen waste and forest biomass waste, respectively. Decentralized power production via the presented routes can complete a sustainable energy mix including photovoltaics or wind power generation. Bioenergy is storable solar energy and, therefore, a flexible and constant source of sustainable energy. Biomass power generation can balance performance fluctuations of photovoltaic and wind systems and is an essential part of reliable energy systems. Rural areas derive of excellent frame conditions by providing waste from forestry and agricultural production. A sustainable and reliable energy mix for Sunyani, which is based on local resources, can solve environmental problems like organic waste accumulation and hazardous open sawdust fires. Furthermore, positive effects on local markets are possible. The presented study introduces the design of an integrated research plant for electricity, heat and cold.

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Declaration of interests

None.

References

[1] Dumenu WK, Obeng EA. Climate change and rural communities in Ghana: Social vulnerability, impacts, adaptations and policy implications. Environ Sci Policy 2016;55:208–17.
[2] Srivastava AK, Mboh CM, Zhao G, Gaiser T, Ewert F. Climate change impact under alternate realizations of climate scenarios on maize yield and biomass in Ghana. Agric Syst 2018;159:157–74.
[3] Velhagen K. SREP INVESTMENT PLAN FOR GHANA: Scaling-up Renewable Energy Program in Ghana (SREP) Investment Plan; 2015, ⟨https://www.climateinvestmentfunds.org/sites/default/files/meeting-documents/srep_13_4_srep_investment_plan_for_ghana_0.pdf⟩, accessed 24 January; 2018.
[4] Dasappa S. Potential of biomass energy for electricity generation in sub-Saharan Africa. Energy Sustain Dev 2011;15(3):203–13.
[5] Energy Commission. Ghana - Sustainable Energy for All: Action Plan; 2012; 2018. ⟨http://www.energycom.gov.gh/files/SE4ALL-GHANA%20ACTION%20PLAN.pdf⟩, accessed 24 January.
[6] Sakah M, Diawuo FA, Katzenbach R, Gyamfi S. Towards a sustainable electrification in Ghana: a review of renewable energy deployment policies. Renew Sustain Energy Rev 2017;79:544–57.
[7] Duku MH, Gu S, Hagan EB. A comprehensive review of biomass resources and biofuels potential in Ghana. Renew Sustain Energy Rev 2011;15(1):404–15.
[8] Energy Commission of Ghana. National Energy Statistics 2008 - 2017: STRATEGIC PLANNING AND POLICY DIRECTORATE; 2018; 2019. ⟨http://energycom.gov.gh/files/ENERGY_STATISTICS_2018_FINAL.pdf⟩, accessed 25 January.
[9] Republic of Ghana. Electricity Supply Plan for the Ghana Power System: A 2018 Power Supply Outlook with Medium Term projections; 2018; 2018. ⟨http://www.energycom.gov.gh/files/2018_Electricity_Supply_Plan.pdf⟩, accessed 28 January.
[10] Ndehedehe CE, Awange JL, Kuhn M, Agutu NO, Fukuda Y. Analysis of hydrological variability over the Volta river basin using in-situ data and satellite observations. J Hydrol: Reg Stud 2017;12:88–110.
[11] Logah FY, Obuobie E, Ofori D, Kankam-Yeboah K. Analysis of rainfall variability in Ghana. Int J Latest Res Eng Comput (IJLREC) 2013;1(1):1–8.
[12] Energy Commission of Ghana. Energy (Supply and Demand) Outlook for Ghana: Final; 2016; 2016. ⟨http://energycom.gov.gh/files/Energy%20Commission%20-%202016Energy%20Outlook%20for%20Ghana_final.pdf⟩, accessed 24 January.
[13] Energy Commission. Strategic National Energy Plan 2006 – 2020: Main Report; 2006; 2019. ⟨http://www.energycom.gov.gh/files/snep/MAIN%20REPORT%20final%20PD.pdf⟩, accessed 27 January.
[14] Energy Commission. Strategic National Energy Plan 2006 – 2020 Annex Four of Four: ENERGY SUPPLY TO THE ECONOMY. Woodfuels and Renewables; 2006; 2019. ⟨http://www.energycom.gov.gh/files/snep/WOOD%20FUEL%20final%20PD.pdf⟩, accessed 27 January.
[15] Energy Commission of Ghana. Strategic National Energy Plan 2006 - 2020: Annex two of four. Energy Supply to the Economy - Electricity; 2006; 2018. ⟨http://energycom.gov.gh/files/snep/electricity%20final%20PD.pdf⟩, accessed 24 January.
[16] Ministry of Energy. National Energy Policy; 2010. ⟨http://www.petrocom.gov.gh/assets/national_energy_policy.pdf⟩, [accessed 24 January 2018].
[17] Kemausuor F, Obeng GY, Brew-Hammond A, Duker A. A review of trends, policies and plans for increasing energy access in Ghana. Renew Sustain Energy Rev 2011;15(9):5143–54.
[18] The Parliament of the Republic of Ghana. RENEWABLE ENERGY ACT 2011: Act 832; 31.12; 2011.
[19] NCCC. Ghana National Climate Change Policy; 2013. ⟨http://www.un-page.org/files/public/ghanaclimatechangepolicy.pdf⟩, [accessed 24 January 2018].
[20] Kemausuor F, Kamp A, Thomsen ST, Bensah EC, Østergård H. Assessment of biomass residue availability and bioenergy yields in Ghana. Resour, Conserv Recycl 2014;86:28–37.
[21] Mohammed YS, Mokhtar AS, Bashir N, Saidur R. An overview of agricultural biomass for decentralized rural energy in Ghana. Renew Sustain Energy Rev 2013;20:15–25.
[22] Arranz-Piera P, Bellot O, Gavaldà O, Kemausuor F, Velo E. Trigeneration based on biomass - specific field case: agricultural residues from smallholder farms in Ghana. Energy Procedia 2016;93:146–53.
[23] Derkyi NSA, Sekyere D, Coffie J. Utilization of Tetrapleura tetraptera waste for energy and climate change mitigation. JENRM 2014;I(1):8–12.
[24] FAO. Global Forest Resources Assessment: Country Report Ghana; 2014; 2015. ⟨http://www.fao.org/3/a-az221e.pdf⟩, [accessed 24 January 2018].
[25] Appiah M, Pappinen A. A review of reforestation approaches in Ghana: sustainability and genuine local participation Lessons for Implementing REDD…. Eur J Sci Res 2015;131(1):70–99.
[26] Vlosky RP. A Strategic Overview of the Forest Sector in Ghana: Working Paper #81; 2007; 2018. ⟨http://www.lfpdc.lsu.edu/publications/working_papers/wp81.pdf⟩, accessed 24 January.
[27] Forestry Commission. Manuals of Procedure for Forest Resource Management Planning in the High Forest Zone of Ghana; 1998; 2018. ⟨http://fcghana.org/assets/file/Publications/Manuals/MOP.pdf⟩, accessed 24 January.
[28] Forestry Commission. GHANA TIMBER INDUSTRY VALUE ADDED PROCESSING STUDY: PART I: INDUSTRY-WIDE SURVEY ON VALUE ADDED PROCESSING OF TIMBER INDUSTRIES IN GHANA; 01.04; 2012.
[29] IEA - International Energy Agency. WEO- Special Report: Energy Access Outlook; 2017.
[30] Frank Eshun J, Potting J, Leemans R. Wood waste minimization in the timber sector of Ghana: a systems approach to reduce environmental impact. J Clean Prod 2012;26:67–78.
[31] Chrzanowska N, Döbbeling N, Neulinger M, Okan-Adjetey PNKM, Wiese K. Sicherstellung einer verlässlichen und bezahlbaren Stromversorgung: Anwendungen erneuerbarer Energien in der Industrie in Ghana: Zielmarktanalyse mit Profilen der Marktakteure, ⟨https://www.giz.de/fachexpertise/downloads/2015-de-ahk-ghana-verlaessliche-stromversorgung.pdf⟩, [accessed 23 January 2018]; 2015.
[32] Eshun JF, Potting J, Leemans R. Inventory analysis of the timber industry in Ghana. Int J Life Cycle Assess 2010;15(7):715–25.
[33] Okai R. Fellowship report: a study on the milling and strength properties of branchwood suggests that logging residues could be used to help meet the timber demands of the downstream processing sector. ITTO Trop For Update 2002;12(1).
[34] Scharai-Rad M, Noack D. Final Report of the Forest Studies: Better Utilization of

Tropical Timber Resources in order to improve sustainability and reduce negative ecological impacts: IITO-PROJECT PO 74 / 90 (F, I);1(2); 1994.
[35] Steffen A. Final Report of the mill studies: Better utilization of tropical timber resources in order to improve sutainability and reduce negative ecological impacts: ITTO-PROJECT PD 74/90 (F, I);1(3); 1995.
[36] World Bank Group. Sawmill Residues Utilization Study - (Volume I - Technical Report); 1988. 〈http://documents.worldbank.org/curated/en/105411468749750285/pdf/multi0page.pdf〉, [accessed 24 January 2018].
[37] Nketiah KS, Bonsu Atakora S, Brew-Hammond A. Ghana Sawmill Energy Efficiency Study; 2001, 〈https://assets.publishing.service.gov.uk/media/57a08d64e5274a27b2001809/R74131.pdf〉, accessed 24 January; 2018.
[38] Amoah M, Becker G, Nutto L. Effects of log export ban policy and dynamics of global tropical wood markets on the growth of timber industry in Ghana. J For Econ 2009;15(3):167–85.
[39] Orwa, et al. Tetrapleura tetraptera. Agrofor Database 2009;4.0.
[40] Boamah F. Imageries of the contested concepts “land grabbing” and “land transactions”: implications for biofuels investments in Ghana. Geoforum 2014;54:324–34.
[41] Aha B, Ayitey JZ. Biofuels and the hazards of land grabbing: Tenure (in)security and indigenous farmers’ investment decisions in Ghana. Land Use Policy 2017;60:48–59.
[42] Amer P. Grow: Nat Middle East 2017.
[43] Tchango J, Bikoï A, Achard R, Escalant JV, Ngalani JA. Plantain: Post-harvest Operations; 1999; 2018. 〈http://www.fao.org/3/a-ax439e.pdf〉, accessed 12 March.
[44] Electricity Company of Ghana Limited. About the Power Sector in Ghana; 2016, 〈http://ecgonline.info/index.php/about-the-power-sector-in-ghana.html〉, [accessed 27 January 2019].
[45] Google LLC. Population in Sunyani - Google-Suche: Mountain View, 〈https://www.google.com/search?Q = population + in + Sunyani&rlz = 1C1GGRV_enDE775DE775&oq = population + in + Sunyani&aqs = chrome.69i57j69i59.662j0j4&sourceid = chrome&ie = UTF-8〉, accessed 27; September 2018.
[46] Henry M, Besnard A, Asante WA, Eshun J, Adu-Bredu S, Valentini R, Bernoux M, Saint-André L. Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. For Ecol Manag 2010;260(8):1375–88.
[47] Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure J-P, Nelson BW, Ogawa H, Puig H, Riéra B, Yamakura T. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 2005;145(1):87–99.
[48] Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M, Martínez-Yrízar A, Mugasha WA, Muller-Landau HC, Mencuccini M, Nelson BW, Ngomanda A, Nogueira EM, Ortiz-Malavassi E, Pélissier R, Ploton P, Ryan CM, Saldarriaga JG, Vieilledent G. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Change Biol 2014;20(10):3177–90.
[49] Feldpausch TR, Banin L, Phillips OL, Baker TR, Lewis SL, Quesada CA, Affum-Baffoe K, Arets EJMM, Berry NJ, Bird M, Brondizio ES, Camargo P de, Chave J, Djagbletey G, Domingues TF, Drescher M, Fearnside PM, França MB, Fyllas NM, Lopez-Gonzalez G, Hladik A, Higuchi N, Hunter MO, Iida Y, Salim KA, Kassim AR, Keller M, Kemp J, King DA, Lovett JC, Marimon BS, Marimon-Junior BH, Lenza E, Marshall AR, Metcalfe DJ, ETA Mitchard, Moran EF, Nelson BW, Nilus R, Nogueira EM, Palace M, Patiño S, Peh KS-H, Raventos MT, Reitsma JM, Saiz G, Schrodt F, Sonké B, Taedoumg HE, Tan S, White L, Wöll H, Lloyd J. Height-diameter allometry of tropical forest trees. Biogeosciences 2011;8(5):1081–106.
[50] Chave J. Generic tree allometric models; 10.05.2014; January 2018. 〈http://chave.ups-tlse.fr/pantropical_allometry.htm#database〉, accessed 23.
[51] Yeboah D, Burton AJ, Storer AJ, Opuni-Frimpong E. Variation in wood density and carbon content of tropical plantation tree species from Ghana. New For 2014;45(1):35–52.
[52] Reyes G, Brown S, Chapman J, Lugo AE. Wood Densities of Tropical Tree Species; 1992, 〈https://www.researchgate.net/publication/237339477_Wood_Densities_of_Tropical_Tree_Species〉, accessed 24 January; 2018.
[53] Döring S. Power from pellets: technology and applications. Heidelberg, New York: Springer; 2013.
[54] Sikkema R, Junginger M, Pichler W, Hayes S, Faaij APC. The international logistics of wood pellets for heating and power production in Europe: costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. Biofuels, Bioprod Bioref 2010;4:132–53.
[55] DIN Deutsches Institut für Normung e.V. Solid biofuels – Determination of moisture content - Oven dry method – Part 2: Total moisture - Simplified method; German version EN 14774-2:2009. Beuth Verlag;75.160.10; 2010.
[56] DIN Deutsches Institut für Normung e.V. Solid biofuels – Determination of ash content; German version EN 14775:2009. Beuth Verlag;75.160.10; 2012.
[57] DIN Deutsches Institut für Normung e.V. Solid Biofuels – Determination of calorific value; German version EN 14918:2009. Beuth Verlag;75.160.10; 2014.
[58] DIN Deutsches Institut für Normung e.V. Solid biofuels – Determination of total content of carbon, hydrogen and nitrogen (ISO 16948:2015); German version EN ISO 16948:2015. Beuth Verlag;75.160.10; 2018.
[59] DIN Deutsches Institut für Normung e.V. Solid biofuels – Method for the determination of ash melting behaviour – Part 1: Characteristic temperatures method; German version CEN/TS 15370-1:2006. Beuth Verlag;75.160.10; 2006.
[60] Spanner Re2 GmbH. STROM & WÄRME AUS HOLZ: DIE HOLZ-KRAFT-ANLAGE, 〈https://www.holz-kraft.com/en/products/hka-35-45-49.html#null〉, accessed 25 June; 2018.
[61] FAO. Food and agriculture data; 2018. 〈http://www.fao.org/faostat/en/#home〉.
[62] DIN Deutsches Institut für Normung e.V. Cereals, cereals-based products and animal feeding stuffs – Determination of crude fat and total fat content by the Randall extraction method. Beuth Verlag;ICS 67.060, [accessed 9 May 2018]; 2016.
[63] VDI-Gesellschaft Energie und Umwelt (GEU). Fermentation of organic materials. Characterisation of the substrate, sampling, collection of material data, fermentation tests. Verein Deutscher Ingenieure e.V., Düsseldorf;ICS 13. 030.30, 27.190, 2016, 〈https://www.researchgate.net/publication/289385029_VDI_4630_Fermentation_of_organic_materials_-_characterisation_of_the_substrate_sampling_collection_of_material_data_fermentation_tests〉, accessed 14 March; 2018.
[64] Raposo F, Fernández-Cegrí V, La Rubia MA, de, Borja R, Béline F, Cavinato C, Demirer G, Fernández B, Fernández-Polanco M, Frigon JC, Ganesh R, Kaparaju P, Koubova J, Méndez R, Menin G, Peene A, Scherer P, Torrijos M, Uellendahl H, Wierinck I, Wilde V de. Biochemical methane potential (BMP) of solid organic substrates: Evaluation of anaerobic biodegradability using data from an international interlaboratory study. J Chem Technol Biotechnol 2011;86(8):1088–98.
[65] StMELF. Biogasanlagen: Berechnung der Gasausbeute von Kosubstraten; 2017. 〈http://www.lfl.bayern.de/iba/energie/031560/〉.
[66] Nielfa A, Cano R, Fdz-Polanco M. Theoretical methane production generated by the co-digestion of organic fraction municipal solid waste and biological sludge. Biotechnol Rep (Amst, Neth) 2015;5:14–21.
[67] FNR. Leitfaden Biogas: Von der Gewinnung zur Nutzung. 6th ed. Fachagentur Nachwachsende Rohstoffe, Gülzow; 2013.
[68] FAO. Food wastage footprint: impacts on natural resources summary report. Rome: FAO; 2013.
[69] Ramage MH, Burridge H, Busse-Wicher M, Fereday G, Reynolds T, Shah DU, Wu G, Yu L, Fleming P, Densley-Tingley D, Allwood J, Dupree P, Linden PF, Scherman O. The wood from the trees: the use of timber in construction. Renew Sustain Energy Rev 2017;68:333–59.
[70] Vassilev SV, Vassileva CG, Song Y-C, Li W-Y, Feng J. Ash contents and ash-forming elements of biomass and their significance for solid biofuel combustion. Fuel 2017;208:377–409.
[71] Akowuah JO, Kemausuor F, Mitchual SJ. Physico-chemical characteristics and market potential of sawdust charcoal briquette. Int J Energy Environ Eng 2012;3(1):20.
[72] Oluoti K, Pettersson A, Richards T. Investigating the morphology and reactivity of chars from Triplochiton scleroxylon pyrolysed under varied conditions. Bioresour Technol 2016;208:94–9.
[73] Ragland KW, Aerts DJ, Baker AJ. Properties of wood for combustion analysis. Bioresour Technol 1991;37(2):161–8.
[74] Adegoke OA, Fuwape J, Fabiyi JS. Combustion properties of Some tropical wood species and their pyrolytic products characterization. Energy Power 2014;4(3):54–7.
[75] Alakangas E. Eigenschaften von festen Biomassebrennstoffen und Vergleich zu fossilen Brennstoffen; January 2018. 〈http://p29596.typo3server.info/fileadmin/Files/Documents/05_Workshops_Training_Events/Taining_materials/german/D19_6_EN_Feste_Biobrennstoffe_Eigenschaften.pdf〉, accessed 23.
[76] Fuwape JA. Utilization of forest and mill residues as industrial fuel. Biol Wastes 1989;30(1):47–51.
[77] Erakhrumen AA. Energy value as a factor of agroforestry wood species selectivity in Akinyele and Ido local government areas of Oyo State 33. Nigeria: Biomass and Bioenergy; 2009. p. 1428–34.
[78] Lasselsberger L. Verbrennungstechnik - Rahmenbedingungen Holzfeuerungen; 2002. 〈http://www.anton-lipp.at/0609/Verbrennungstechnik-Rahmenbedingungen.pdf〉, [accessed 24 January 2018].
[79] Thomas SC, Martin AR. Carbon ContentTree Tissue: A Synth: For 2012;3(4):332–52.
[80] Lamlom SH, Savidge RA. A reassessment of carbon content in wood: variation within and between 41 North American species. Biomass- Bioenergy 2003;25(4):381–8.
[82] Statistics, Research and Information Directorate (SRID). Agriculture in Ghana: Facts and Figures 2015; 2014.
[83] Vögeli Y, Riu Lohri C, Gallardo A, Diener S, Zurbrügg C. Anaerobic Digestion of Biowaste in Developing Countries: Practical Information and Case Studies; 2014; 2018. 〈http://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/publikationen/SWM/Anaerobic_Digestion/biowaste.pdf〉, accessed 8 March.
[84] Addaney M, Oppong RA. Critical issues of municipal solid waste management in Ghana. JENRM 2015;2(1):30–6.
[85] Otache M, Ubwa S, Godwin A. Proximate analysis and mineral composition of peels of three sweet Cassava cultivars. AJOPACS 2017;3(4):1–10.
[86] Christopher I Nwoko, Onyekwe C Enyinnaya, Justus I Okolie, Nkwoada A. THE proximate analysis AND biochemical composition OF THE waste peels OF three cassava cultivars. Int Sci Eng Appl Sci (IJSEAS) 2016;Volume-2(11).
[87] Akinsanmi A Oduje, Oboh G, Akinyemi J Ayodele, Adefegha A Stephen. Assessment of the nutritional, anti nutritional and antioxidant capacity of Uripe, ripe, and over ripe plantain (Musa paradisiaca) peels. Int J Adv Res 2015;3(2):63–72.
[88] Thomsen ST, Kádár Z, Schmidt JE. Compositional analysis and projected biofuel potentials from common West Africanagriculturalresidues. Biomass- Bioenergy 2014;63:210–7.
[89] United States Department of Energy. Absorption Chillers for CHP Systems, 〈https://www.energy.gov/sites/prod/files/2017/06/f35/CHP-Absorption%20Chiller-compliant.pdf〉, accessed 27; September 2018.