Crop Residues Utilisation for Renewable Energy Generation in Ghana: Review of Feedstocks Assessment Approach, Conversion Technologies and Challenges*

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Abstract

Crop residues have a significant role to play in the quest to provide off-grid and mini-grid electricity for unelectrified rural agricultural communities in Ghana. The aim of the study was therefore to review available literature on current state of art of crop residues assessments and utilisation for thermochemical energy generation in Ghana. Overall, 20 relevant literature were identified. The study revealed that, the level of crop residue assessment is on theoretical and technical assessment, employing either field survey or statistical modelling methods. There was major difference between quantities of residues reported due to differences in methods, crop production figures, Residue-to-Product Ratio (RPR) and recoverability ratio. The Northern, Brong-Ahafo and Eastern regions have the highest potential in terms of total residues. The major crop residue types that were identified to be underutilised and therefore available for energy generation include, rice husk, cassava peels and oil palm residues. Fourteen biomass energy installations using thermochemical conversion technologies with total installed capacities of 10.7 MW were identified. These consist of six biomass powered cogeneration plant, three gasifiers, four biomass boilers and one hybrid solar biomass dryer. The major challenges identified for these installations were: unsustainable biomass supply, lack of tailor-made technology to suit locally available residues and inability of conversion technology to utilise all available residues. Further studies are required particularly on the determination of residue to product and recoverability ratios across communities and districts as well as economic and sustainable residue assessments.

Keywords : Crop Residues, Quantities, Assessments, Conversion Technologies

1 Introduction

Energy is one of the major challenges faced by the world today, affecting all aspects of our lives. One of the significant drivers of socio-economic development of a country is the country's access to energy. Many countries in Sub-Saharan Africa (SSA) are faced with several problems which cuts across key economic sectors. In many cases, access to energy is the root of these challenges. Access to energy, particularly electricity, not only boost social welfare, but it also helps to address challenges within other sectors of the economy, such as the provision of better healthcare, education and employment among others. Worldwide, about 1.5 billion people have no access to electricity, with 1 billion more having access only to unreliable electricity networks (Panos *et al.*, 2016). SSA contributes 57 % of global electricity access deficit, i.e., 609 million people do not have access to electricity as at 2014 (Hamilton and Kelly, 2017). Ghana, just like many other SSA countries, is rich in energy resources, but very poor in energy supply. Even though the country has seen increase in electricity access from 23.5 % in 1990 to 82.5 % in 2016 in the urban areas, and 66.65 % in the rural areas (Kumi, 2017). Efforts to ensure overall electricity access require increase in electrification of rural communities through the provision of on- and off-grid electricity solutions.

The principal sources of electric power generation in Ghana are fossil-powered thermal power and hydroelectricity plants. These consist of three hydro power plants contributing 35.92 % of installed generation capacity and thirteen thermal plants with 63.57 % of installed capacity. Grid-connected solar plants contribute 0.51 % of installed capacity (Anon., 2018a). Even though installed capacity is much higher than peak demand, the electricity sector is sometimes faced with supply challenges, resulting from challenges in fuel procurement to run the thermal plants. This has often resulted in interruption in electricity supply. In view of the challenges coupled with diminishing fossil fuel sources as well as concerns about climate change, renewable energy has attracted much attention in recent years in the country.

Biomass, in the form of firewood and charcoal, is the main fuel for cooking and other heat applications in SSA (Prasad, 2011), and is the most consumed fuel in Ghana, accounting for close to 40.5 % of total energy consumption in the country (Anon., 2018b). Current pattern of biomass utilisation in Ghana is, however, unsustainable and presents associated environmental and health issues (Anenberg *et al.*,

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2017). It contributes to climate change at regional and global levels. Over the years, efforts have been focused on using renewable energy to replace these traditional energy sources using first generation bioenergy feedstocks such as sugar cane, cassava, oil palm and cereal grains (Kemausuor *et al*., 2013; Osei *et al*., 2013). However, producing biofuels from these feedstocks present social challenges with respect to land grabbing that could potentially cause food supply shortages (Schoneveld *et al*., 2011). Second generation feedstocks such as Jatropha curcas Linnaeus has also been shown to be economically feasible on the commercial scale by adapting the right farming models and valorisation of by-products (Osei *et al*., 2016). Current efforts have, however, been focused on second generation feedstocks including agricultural residues such as rice husk, maize stover, maize cobs, cassava peels, wood processing waste etc. These residues are potential alternatives to the use of firewood and charcoal and can provide clean and environmentally benign sources of energy for domestic cooking and heat for industrial purposes and electricity generation particularly in unelectrified rural communities.

Agriculture plays a significant role in the economy of most developing countries. Particularly in SSA, the agricultural sector employs more than half of the total work force (Anon., 2016a). The activities in the sector result in the generation of large volumes of agricultural residues from crop and animal. Crop residues are the non-edible plant parts of crops which are left in the field after harvest or after primary processing such as dehusking and/or shelling. Perennial plantation crops e.g. coconut, cocoa, oil palm, etc., generate substantial quantities of residue through replanting, pruning and processing activities (Anon., 2013). Annual crops such as rice, soybean, maize cassava, etc., presents prospect for field and process-based residues besides the use of the crops itself. Even though most crops produce some form of residue, not all crop residues can be effectively utilised for energy production due to the nature of the residue produced or its composition. Based on the potential for utilisation, residues have been categorised into three pathways. The first pathway consists of residues left on the farm and in the immediate vicinity of farm communities. Examples are maize stover, sorghum stalks, millet straw, cassava stems and plantain trunks (Kemausuor, 2015). The second pathway consists of residues left at primary/secondary processing sites, which may also be on the farm, within the farming community or at a processing facility. These residues include maize cobs, maize husks, rice husks, and cassava peels etc. The third pathway consists of residues left at places of consumption, including cassava peels, plantain peels, yam peels, cocoyam peels, and potato peels. These residues, which could also be referred to as process residues, are scattered in homes and restaurants and are only available in small quantities. They are difficult and expensive to collect and often end up in Municipal Solid Waste (MSW) stream (Kemausuor, 2015).

These crop residues can be used to sustainably provide off-grid energy solutions to rural communities using a number of conversion technologies. These technologies are at different levels of advancement in developing countries (Anon., 2017; Jacobi, 2011). The technologies are grouped under two main categories: biochemical and thermochemical conversion technologies (Saidur *et al*., 2011). Biochemical treatment technologies are designed and engineered for natural biological process. Current developed waste to energy biological treatment methods include anaerobic decomposition, microbial fuel cell and biofuel production from waste lignocellulosic materials. Anaerobic decomposition is one of the most widely used waste conversion technologies in developing countries mostly from agricultural residues (Kranert *et al*., 2012). The process involves digestion of organic materials by anaerobic bacteria in airtight environment referred to as a bio-digester. The process occurs in four main steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Biogas is produced at the end of these processes which can be used directly for heat applications e.g. cooking. Through the removal of carbon dioxide and hydrogen sulphide, it can be used in internal combustion engines for electricity generation as well as transport purposes. Biogas units, especially domestic biogas, are widespread in several developing countries, particularly in Asian countries such as China, Nepal, Vietnam and India. The technology is also being used in African countries including Ghana (Rakotojaona, 2016).

Bioethanol production involves hydrolysis (by enzymatic treatment), fermentation (by use of microorganisms) and distillation. Lignocellulosic (e.g. crop residues) are preferred as feedstock for bioethanol owing to the disadvantages of first-generation feedstocks. Kim and Dale (2004) estimated that lignocellulosic biomass could produce up to 442 GL/year of bioethanol from crop residues. In most developing countries, especially in SSA, these crop residues are left on the farm after harvest. The technology has, however, not developed in developing countries as compared to biogas production due to challenges such as food security, land availability, simplicity of the technology and government policies (Kim and Dale, 2004; Deenanath *et al*., 2012).

Thermochemical processes for the conversion of crop waste into energy include combustion, gasification and pyrolysis. Combustion is the most common technology for treating agriculture residues. Incineration is the combustion of waste using excess oxygen (air) to ensure complete combustion at temperature above 850 °C with the generation of thermal energy, flue gas, bottom and fly ash. Direct combustion of agriculture residues for energy generation is well established (Hawkes *et al*., 2014). In many countries, burning agricultural waste, such as stalks, grasses, leaves and husks, continues to be the easiest and least expensive way to reduce or eliminate the volume of combustible materials produced by agricultural activities. Challenges with the use of crop residues for combustion is its low bulk densities and low calorific values of some residue types. The use of boilers for steam and electricity generation has also developed particularly with the use of Combined Heat and Power (CHP) generation systems. This process generates electricity as well as process heat, thereby increasing the overall conversion efficiency. The capacities of combustion-based generation should be at least 1MWe to make economic sense for its implementation (Otchere-Appiah and Hagan, 2014). However, it has been reported that, the electric power demand in remote unelectrified communities in Ghana is within the range of 10 kWe to 100 kWe (Otchere-Appiah and Hagan, 2014), making combustion-based technologies not feasible for small scale off-grid electricity solutions in Ghana.

Pyrolysis is the thermal treatment of biomass in the absence of oxygen and results in the production of bio-oil, gases and bio-char. The oil can then be used as a fuel to generate electricity. Pyrolysis is a subset of gasification systems. During this process unlike gasification, the partial combustion is stopped at a lower temperature (450 °C to 600 °C). There are multiple facilities in the pilot and commercialisation stages producing ethanol from crop residues using pyrolysis (Jacobi, 2011).

Gasification on the other hand occurs at higher temperatures and in less oxygen-restricted conditions than pyrolysis and leads to the formation of a synthesis gas (syngas) with the main constituent being hydrogen and carbon monoxide. There are three main configurations of gasifiers; "fixed bed", "fluidised bed" and "entrained flow" (Anon., 2012). Syngas can be used directly for heat applications such as cooking, drying of crops, etc. Gasifier stoves for cooking is common in some developing countries, particularly Asia. When syngas is appropriately cleaned to remove tar and carbon dioxide, it can be used in combustion engines, micro-turbines, fuel cells or gas turbines. Rice husk gasification systems have been commercially established in China, India and South-East Asia successfully which power a small industry or a community. A typical commercially established plant varies between 100 - 400 kWe, however, plants as small as 10 kW and as large as 2 MW have been established (Ramamurthi *et al*., 2016).

The available conversion technologies for crop residues have the potential to provide several socio-economic benefits including: power modern irrigation facilities to cultivate crops during the dry season, establishment of small and medium scale enterprises, hospitals and other social interventions due to access to electricity. Farmers households would also have the opportunity to become suppliers of biomass resources for energy production and thereby broaden their income generation sources; this will also enable the use of crop handling and pre-processing machinery and the collection and utilisation of crop residues would also help curb bush fires that often start with residues burnt on harvested fields and spread to forests and unharvested fields during the dry season (Arranz-Piera *et al*., 2016). Constraints to crop residue utilisation in Ghana can be attributed to identification of resources locations and providing good estimation of available crop residues coupled with lack of tailor made locally available, efficient conversion technologies. A number of studies have however reported the potential from the perspective of resource availability (Kemausuor *et al*., 2014; Mohammed *et al*., 2013; Duku *et al*., 2011) which is mainly based on theoretical and technical estimation of quantity of crop residues available. To present the actual potential, location specific crop residue potential must be investigated. The potential of crop residues for renewable energy generation have not been fully exploited owing to reasons previously indicated. This study is, therefore, aimed at providing current state of art of crop residues utilisation for energy generation. Specifically, the study seeks to:

(i) Review current approach and method employed in crop residue assessment in Ghana;
(ii) Determine quantity of crop residues available and identify residues with good prospects for renewable energy generation in Ghana; and
(iii) Identify crop residues conversion technologies in use and their challenges.

This study is expected to identify the gaps for current crop residues estimation approach and present locations where crop residues are available as well as their current uses so as to present a true reflection of crop residues potential. The study is also expected to present current conversion technologies in use across the country to identify challenges and gaps, and to guide the development of effective and appropriate conversion technology. The outcome of the study is expected to contribute significantly to the sustainable utilisation of crop residues for energy generation as it will provide an overview of residues available, current conversion technologies as well as success stories to draw lessons for policy makers, technologists and other relevant stakeholders. This is in line with the governments of Ghana's efforts to develop bioenergy conversion technologies as part of the renewable energy masterplan (Anon., 2019a).

2 Resources and Methods Used

2.1 Resources

The materials used for the study were information gathered from journals, websites and unpublished materials relating to crop residues utilisation for renewable energy generation in Ghana. These materials were obtained from databases which include; ScienceDirect, Google Scholar, CiteSeer, Scopus, government websites, policy papers and institutional databases such as The Ghana Energy Commission, Ministry of Energy, the International Energy Agency (IEA), and Centre for Renewable Energy and Energy Efficiency (ECREEE) of the Economic Community for West African States (ECOWAS).

2.2 Methods Used

The approach was to review materials, comparing and considering published results. Biomass to energy technologies in this study is focused on thermo-chemical conversion due to its easy use for solid crop residues. Moreover, bio-chemical conversion processes, particularly biogas has been well documented (Kemausuor *et al*., 2018a).

The approach was to utilise a number of search engines aimed at identifying all reports and academic literature related to the topic between the years 2011 and 2019, based on a similar approach by Hall and Buckley (2016), and Kemausuor *et al.* (2018b). In all cases, the following phrases, among others, were considered: "crop residues assessment in Ghana", "methods employed for estimation of crop residues in Ghana", "estimation of crop residues quantities and its potential for energy generation in Ghana" "conversion technologies for crop residues in Ghana" "successful crop residues conversion technologies employed in Ghana", "challenges with crop residue conversion technologies in Ghana". Overall, 20 papers were identified (see Table 1 and 2) with 13 studies relating to crop residue assessment and 7 on conversion technology for crop residues in use in Ghana. These papers were then analysed.

Table 1 Studies on Crop Residues Assessments in Ghana

Reference	Type of potential	Quantities (t/yr)	Area under consideration
Aboagye *et al.* (2017)	Theoretical ^{sm}	59 636	National
Arranz-Piera *et al.* (2016)	Theoretical ^{sm}	499 t/10 ha farm	11 districts
Duku *et al.* (2011)	Theoretical ^{sm}	4 821 600	National
Mohammed *et al.* (2013)	Theoretical ^{sm}	6 648 098	National
Osei *et al.* (2013)	Theoretical ^{sm}	215 091	1 District
Addo *et al.* (2014)	Technical &theoretical ^{F}	127 794	National
Ayamga *et al.* (2015)	Technical ^{sm}	108 723	District
Boateng (2016)	Technical ^{sm}	25 675	District
Darkwa and Kemausuor (2016)	Technical ^{F}	6 202	National
Ewusi-Mensah *et al.* (2016)	Technical ^{F}	41 471	National
Kemausuor *et al.* (2015)	Technical ^{F}	2 404	Specific project cases
Kemausuor *et al.* (2014)	Technical ^{sm}	18 862 282	National
Otchere-Appiah and Hagan (2014)	Technical ^{sm}	382 629	Regional

Note: ^{sm} and ^{F} indicate the method employed being statistical modelling and field-based assessment respectively

Table 2 Crop Residue Conversion Technologies in Use Across Ghana

Conversion Technology	Capacity (kWe)	Reference
Gasifier	20	Commeh *et al*. (2019)
Gasifier	120	Anon. (2016b)
Gasifier	24.8	Owen and Ripken (2017)
Biomass Cogeneration	2 500	Anon. (2016b)
Biomass Cogeneration	1 000 [1]	Addo *et al.* (2014)
Biomass Cogeneration	1 200 [2]	Anon. (2016b)
Biomass Cogeneration	800	Addo *et al.* (2014)
Biomass boiler	15 tonnes/hour Boiler for steam generation	Anon. (2016b)
Biomass Cogeneration	1 000	Anon. (2016b)
Biomass Cogeneration	4 000 [3]	Anon. (2019a)
solar biomass hybrid dryer	-	Anon. (2016b)
Biomass boiler	8 tonnes/hour steam boiler	Anon. (2019b)
Biomass boiler	-	Anon. (2018c)
Biomass Boiler	6 tonnes/hour boiler	Anon. (2015)

[1] Currently run on 500 kW
[2] Currently uses 610 kW
[3] Currently uses 2.5 MW

3 Results and Discussion

3.1 Overview of Methods and Approach to Crop Residue Assessment in Ghana

Thirteen published literature that reports on assessment of crop residues availability for energy generation in Ghana at both theoretical and technical level were identified. The assessments were done at the national, regional and district levels and employed different methods. Five of the studies used theoretical assessment employing statistical modelling to estimate available crop residue potential based on crop production statistics (see Equation 1). The theoretical potential is straight forward since it takes into consideration the total available biomass based on crop production statistics. To determine theoretical residues potential, crop production statistics is multiplied by the Residue-to-Product Ratio (RPR) of the various residue types. RPR simply means the ratio by weight of a particular residue generated by a certain crop to the amount of crop harvested. For the same residue types, RPR could vary for different farms, communities and countries due to differences in moisture content at time of measurement, yield of crops, and yield of biomass, which all depend on climatic conditions and the level of farm management (Ayamga *et al*., 2015; Kemausuor *et al*., 2014).

The choice of an RPR is therefore important in determining the realistic theoretical potential. Out of the five studies that determined theoretical potential, three used RPR determined from experimental studies in Ghana whiles the other two used RPR from literature determined outside Ghana. RPR determined in Ghana for various crop residues have been shown to vary from farms and ecological zones, which is mainly dependent on farming practices (e.g. use of fertilizers) and climatic conditions (Ayamga *et al*., 2015; Kemausuor *et al*., 2014; Osei *et al*., 2013).

$$P_{AR} = \sum_{i=1}^{n} (C_i \times RPR_i) \qquad (1)$$

where: P_{AR} is the annual crop residue potential, C_i is the annual end product produced (e.g. for rice mills the end product is milled rice) and RPRi is the residue to product ratio of crop i. Factor n is the total number of residue categories for each crop.

Seven studies determined technical residue potential. To determine technical residues, recoverability fraction indicating the fraction of the residues that can realistically be collected are multiplied by the theoretical residue quantities (Smeets *et al*., 2007). The choice of recoverability ratio is therefore very critical in determining the realistic technical residue potential. This is influenced by crop type, soil type, typical weather conditions, and the tillage system used and requires a detailed procedure to determine these ratios (Kludze *et al*., 2010).

Out of the studies that determined technical residue potential, four employed the use of statistical analysis and applying recoverability fraction to the optimum residues that can be generated using Equation 2. These studies used recoverability ratios presented in literature outside Ghana. However, as indicated, the choice of recoverability ratio is terrain and country specific linking to socio-cultural and farming practices. Three of the studies employed field survey with the use of structured questionnaire and field measurement when necessary. These assessments took into consideration the residues that can be available for energy generation owing to site specific residue usage and therefore such studies are also categorized as technical residue potential.

$$P_{AR} = \sum_{i=1}^{n} (C_i \times RPR_i \times \eta_{rec\ i}) \qquad (2)$$

where, $\eta_{rec\ i}$ is the recoverability fraction of each residue type.

None of the studies determined economic, implementation and sustainable biomass potentials. This level of assessment is required to presents realistic and economically viable quantities of residues that can be assessed for bioenergy projects. Energy projects are not likely to succeed if this level of assessment is not done thoroughly due to unsustainable feedstock supply.

3.2 Challenges with Current Crop Residues Assessment Studies in Ghana

Table 1 presents a summary of quantities of crop residues and the corresponding level of assessment at the national, regional and the district level. As shown in Table 1, there are significant differences in the quantities of crop residues generated even at the same level of assessment, areas under consideration (i.e. national, regional or district level) and crop residue types. The underlying causes of variation in the reported yield of crop residues were identified to be:

(i) Different methods of residue assessment;
(ii) Different crop production figures in situations where statistical modelling approach is used;
(iii) Variation in the RPR; and
(iv) Variation in the recoverability ratios.

3.2.1 Methods of Residue Assessments

Based on the reported studies, two main methods were employed to determine theoretical and technical levels of residue assessments. These are field surveys and statistical modelling of which were respectively used by four and nine of the studies reviewed. Statistical modelling approach usually quantifies the residues at an aggregated level, often at the district, regional, or national level whiles field-based studies determines residue availability at specific location e.g. agro-processing industries. Each of the approaches have significant effects on the reported quantities of the same residue types. Statistical modelling approach generally presents higher quantities of residues than field surveys for the same level of residue assessment and residue type. There are therefore differences between the quantities of residues using these two approaches. Kemausuor *et al.* (2014) reported technical quantities of rice husk to be 85 738 tonnes by employing statistical modelling approach. Similarly, field study by Addo *et al.* (2014) presented total annual rice husk to be 3 578 tonnes covering ten agro-processing industries across the country. The wide variation of residues quantities despite determining the same levels of residues is mainly contributed by the method employed.

The field study approach was not exhaustive enough to capture all agricultural and agro-processing industries. The statistical modeling also accounts for all other small farm residues whereas the field study only targeted large farms, where it is more realistic to obtain residues. However, the statistical modelling approach might have also overestimated the available residues and presented residues which may not be available on the field as it might have been used for other purpose. The field study, therefore, helps to establish the current uses of the residues in order to estimate available quantities that can be available for energy generation. For example, Kemausuor *et al.* (2015) through field survey estimated total annual quantities of cassava peels in two well-known communities for gari processing in the Techiman Municipality to be 4 545 tonnes, the study however, revealed that 2 141 tonnes is collected for livestock feeding and therefore only 2 404 tonnes can be available for energy generation.

3.2.2 Different Crop Production Figures

Crop production figures play a critical role in determining available crop residues particularly when the statistical modelling method is employed as shown in Equations 1 and 2. Therefore, the variations of the various levels of theoretical and technical potential is contributed hugely by the quantities of crop produced within the year of assessment. Duku *et al.* (2011) using maize production figures of 1 100 000 tonnes in the year 2008 and RPR of 1.5 estimated the theoretical quantities of maize stalk to be 1 650 000 tonnes. Similarly, Mohammed *et al.* (2013) using maize production figures of 1 872 000 tonnes in the year 2010 and RPR of 1.4 reported quantities of maize stalk to be 2 620 800 tonnes. The difference between maize stalk for the two studies can hugely be attributed to the crop production figures used as the RPRs were almost the same with slight variation. It is, therefore, critical in reporting the available quantities of residues, the year in which the estimation was done must be indicated. It may be important to use average crop production figures over a period to present average annual biomass residues instead of using production figures for a single year. However, most of the studies used crop production figures for a single year for their analyses (Ayamga *et al.*, 2015; Mohammed *et al*., 2013; Boateng, 2016; Osei, 2013 Duku *et al*., 2011).

3.2.3 Variation in the Residue to Product Ratio (RPR)

RPR values for a specific residue type is affected by environmental, agricultural practices, farming methods among other as explained earlier. Some studies relied on RPR from literature outside Ghana (Aboagye *et al*., 2017; Otchere-Appiah and Hagan 2014; Duku *et al*., 2011) and others from experimental studies in Ghana (Ewusi-Mensah *et al*., 2016; Boateng, 2016; Ayamga *et al*., 2015; Osei, 2013). In some cases, there is significant difference between the figures used from literature and the one from experiment. For example, as presented in Table 3, RPR of maize stalk of 1.0 was used by Otchere-Appiah and Hagan (2014), however, Kemausuor *et al.* (2014) and Ayamga *et al.* (2015), through field experiment reported RPR of 1.15 and 1.37 respectively. Mohammed *et al.* (2013) also used RPR of 1.4 for sorghum stalk, but field experiment by Ayamga *et al.* (2015) estimated RPR of 4.75. Moisture content at which the RPRs were determined also played a role in the differences.

Table 3 RPR Values of Some Selected Crop Residues Used in the Studies in Ghana

Crop type	Residue type	RPR from literature	RPR field experiment
Maize	Stalk	1.5 [a], 1.4 [b], 1.0 [e]	1.15 [c]; 1.37 [d]
	Husk	0.25 [e]	0.23 [c]; 0.26 [d]
	Cobs	-	0.57 [c]; 0.25 [d]
Rice	Husk	-	0.23 [d]
	Straw	1.5 [a], 1.5 [b]	3.05 [d]
Sorghum	Stalk	2.62 [a] 1.4 [b]	4.75 [c]
	Husk		0.14 [c]
Cocoa	Cocoa pods	1 [a]	1.00 [d]

[a] (Duku *et al*., 2011)
[b] (Mohammed *et al.* (2013)
[c] (Ayamga *et al*., 2015)
[d] (Kemausuor, 2015)
[e] (Otchere-Appiah and Hagan, 2014)

Most RPR values that were determined through experiments in Ghana were done in few districts across Ghana. However, Kemausuor *et al.* (2014) reported RPR values in 16 different towns in eight districts and five out of then ten regions in the country. The study revealed that, RPR values for the same residue types varied across the various town, districts and regions. Therefore, in the quest to estimate residue potential, localized RPR for communities and district is expected to present realistic residue potential. Therefore, more studies are required to determine RPR values across Ghana.

3.2.4 Variation in the Recoverability Ratios

In determining technical residue potential, recoverability ratio is a critical parameter (Zheng *et al*., 2010; Lemke *et al*., 2010). Groode and Heywood (2008) suggested an allowable removal rate of crop residues of 30 – 50 %.

These ratios can be determined through field surveys using questionnaire administration. Table 4 presents recoverability ratios used by Kemausuor *et al*. (2014). The ratios for the various crop residues types were determined based on two assumptions: the first is that some residue will be left on farm plots for re-fertilisation, in line with global agricultural principles. The second assumption is that there will be practical challenges when collecting field residues, due to poor road conditions to, especially, small-holder farms in rocky and mountainous agricultural fields. In an assessment of maize residues for energy production in the Eastern region of Ghana, the Kumasi Institute for Technology, Energy and Environment (Anon., 2009), used 80 % recoverability fraction, taking into consideration the fact that farming in Ghana is largely no-tillage and with no existing regulation for residue management. Ayamga *et al.* (2015) assumed 10 %, 25 % and 40 % availability of residues representing low scenario, medium scenario and high scenario, respectively for the residue's types. Even though the analyses present various scenarios for the recoverability fraction, the study assumed the same recoverability fraction for all the residue types. This may not present a true reflection of the available residues as the rate at which each residue type can be recovered is not the same. All the recoverability ratios used for the studies reviewed were not based on field survey but rather based on assumptions. However, in order to determine realistic residue potential recoverability ratio must be determined based on field survey and measurement (Kludze *et al*., 2010).

Table 4 Recoverability Fraction of Selected Residues

Crop type	Residue type	Recoverability fraction
Maize	Stalk	0.35
	Husk	0.80
	Cobs	0.80
Rice	Husk	0.80
	Straw	0.35
Cassava	Peelings	0.20
Sorghum	Stalk	0.50

(Kemausuor *et al*., 2014)

3.3 Crop Residues Variations in Region, District and Communities in Ghana

3.3.1 Agricultural Crop Residues Availability at Regional and District Levels

The major crop residue types that were identified to be underutilised and therefore available for energy generation include: rice husk (Ewusi-Mensah *et al*., 2016), cassava peels (Darkwa and Kemausuor, 2016) and oil palm residues (Addo *et al*., 2014). Table 5 presents the quantities of crop residues generated in the various regions in Ghana based on technical residue assessment reported by Kemausuor *et al.* (2015). The residues taken into consideration in Table 5 include: cassava peels, yam peels, maize husk, stalk and cob, plantain trunk and leaves, groundnut stalk and shell, rice straw and husk, sorghum straw and shells, cowpea shells, millet stalk, sugarcane bagasse, coconut husk and shells, cotton stalk and sweet potato straw, oil palm empty fruit bunch, cocoa pods and cotton stalk.

The Northern, Brong Ahafo and Eastern region have the highest potential in terms of total residues. Together they account for more than 58 % of the crop residues available in the country. The Eastern and Brong Ahafo regions rank among the top five regions with the highest total residues and residue densities and therefore make interesting cases for further study and more detailed district level analysis. Districts with high residue potentials are located in the Eastern, Brong Ahafo and Northern regions. The greatest amount of residue is produced in the Afram Plains with residue potential of 450 000 tonnes from different crops (Kemausuor, 2015).

Table 5 Agricultural Residue Availability at Regional Levels

Region	Quantity of waste generated (t/yr)
Eastern	2 943 424
Central	1 191 286
Upper East	842 322
Brong-Ahafo	3 647 669
Ashanti	1 952 738
Upper West	1 301 397
Volta	1 172 363
Northern	3 780 136
Western	902 252
Greater Accra	67 622

(Kemausuor, 2015)

3.3.2 Specific Locations in Ghana where Agricultural Residues can be Assessed

The regional and district crop residue potential give an overview of the potential at regional and district levels but not specific locations where the residues can be accessed which is important if the residues are to be used for energy generation. Clustered small, medium, and large-scale farms offer the largest opportunity for sustainable and economically viable option for energy generation from crop residues (Arranz-Piera *et al*., 2017). Addo *et al.* (2014) reported large-scale irrigation schemes in the country generate substantial quantities of rice straw and husk, maize stalk and cobs that can be used for energy generation. Kpong, Tono and Afife/Whetta irrigated farms respectively generates 31 858; 17 640 and 14 616 tonnes of waste annually with the potential of each capable of generating 1 MWe of electricity (Addo *et al*., 2014). The potential of small-scale clustered farms in Ghana has also been investigated. Arranz-Piera *et al.* (2017) estimates that, in most districts, a minimum number of 22-54 (10 ha) farms would need to be clustered to enable an economically viable biomass supply for a 1000 kWe plant.

Table 6 presents crop residue potential from various agro-processing industries in Ghana. Regions in Ghana with most potential in terms of un-used residue potential are the Northern, Volta, Ashanti and the Brong-Ahafo regions. Even though the Western region has the largest quantities of agro-process residue, most of them are utilised for energy generation particularly in the oil palm industries. Rice husk/bran, cassava peels, cocoa pods, shea butter cake have been identified to be the agro-processing residues with the most potential for energy generation due to their availability. Fig. 1 presents contributions of the various regions and district to the total quantity of agro-process residue in Ghana.

3.4 Energy Conversion Technologies for Crop Residues in Ghana

3.4.1 Proposed Conversion Technologies

Based on the various characteristics of the residue types and their availability, a number of studies have proposed technologies that can be technically feasible for implementation in Ghana (see Table 7). Bioethanol (Ayamga *et al*., 2015; Mohammed *et al*., 2013), biogas (Kemausuor *et al*., 2018a; Kemausuor *et al*., 2014), fast pyrolysis (Bio-oil) (Aboagye *et al*., 2017), pelletisation (Mohammed *et al*., 2013) gasification (Otchere-Appiah and Hagan, 2014) and combined heat, power and cold systems have been proposed (Arranz-Piera *et al*., 2016). The potential for cogeneration and even trigeneration from clustered agricultural waste in some small holder farms is high. Techno-economic results show that 600 kW and 1 MW CHP plants run on local agro waste are feasible in certain rural districts in Ghana (Arranz-Piera *et al*., 2016).

Table 6 Quantities of Agro-Process Residue Generated in the Various Region

Region	Number of agro-processing industries	Quantities of process residue generated (t/yr)	Process residue types
Ashanti	18	29 583	Rice husk, cassava peels, Empty fruit Bunches (EFB), cocoa beans shells
Brong-Ahafo	6	5 583	Cassava peels
Central	2	567	Cassava peels
Eastern	7	2 898	Rice husk/bran
Northern	8	48 118	Rice husk/bran, cotton mote & trash, cassava peels, shea butter cake
Upper East	2	291	Rice husk, cotton motes and trash
Volta	10	25 381	Rice husk/bran
Western	2	157 300	EFB, Over aged Rubber plantation

(Darkwa and Kemausuor, 2016; Ewusi-Mensah *et al.*, 2016; Wunder, 2016; Addo *et al.*, 2014)

3.4.2 Crop Residues Conversion Technologies in Use in Ghana

Overall, fourteen biomass energy installations using thermochemical conversion technologies were identified (see Table 2). These consist of six biomass powered cogeneration plants for both electricity and steam generation, three gasifiers for electricity generation, four biomass boilers for steam generation and one hybrid solar biomass dryer for heat generation for maize drying. The plants have a total installed capacity of 10.7 MW. Large-scale oil palm industries contribute about 10.5 MW of this installation (see Fig. 2). None of these plants are providing off-grid or mini-grid electricity solutions for communities in Ghana. These installations are industry based providing heat and electricity for their operations. However, some oil palm processing companies provides electricity to nearby communities for free or at a minimal cost.

Crop residues used by these plants are presented in Fig. 3. Residues from oil palm contribute 64.3 % of all the residues types used in nine out of the fourteen installations reviewed. This is attributed to the residues been available in one location and the corresponding need for electricity and steam by these companies. Residues such as cassava peels, rice husk, maize cobs are generated in large volumes annually but are not utilised extensively mainly due to their dispersed nature as a result of the various farming systems practiced in Ghana. A facility located at Ejura Sekyedumase in the Ashanti region of Ghana is among only two facilities that were identified to utilise maize cobs for clean energy generation but in smaller quantities (i.e. 30 kg/batch of drying). Arranz-Piera *et al.* (2016), however, reported good technical and economic prospects for clustered small holder and irrigation farms in some districts and communities in Ghana.

3.4.3 Challenges with Crop Residues Conversion Technologies in Use in Ghana

A number of technical challenges have been identified to hinder the smooth operations of the conversion technologies presented in the previous section leading to its low adaptation. The current conversion technologies being used can be upgraded to increase efficiency and utilise unused biomass resources. For example, Benso Oil Mills Limited has installed capacity of 1 MW but currently generates 500 kWe due to the inability of the boiler to use EFB (Anon. 2016b). This can be done by using boilers that can accept all residues types particularly fiber, shells and EFB.

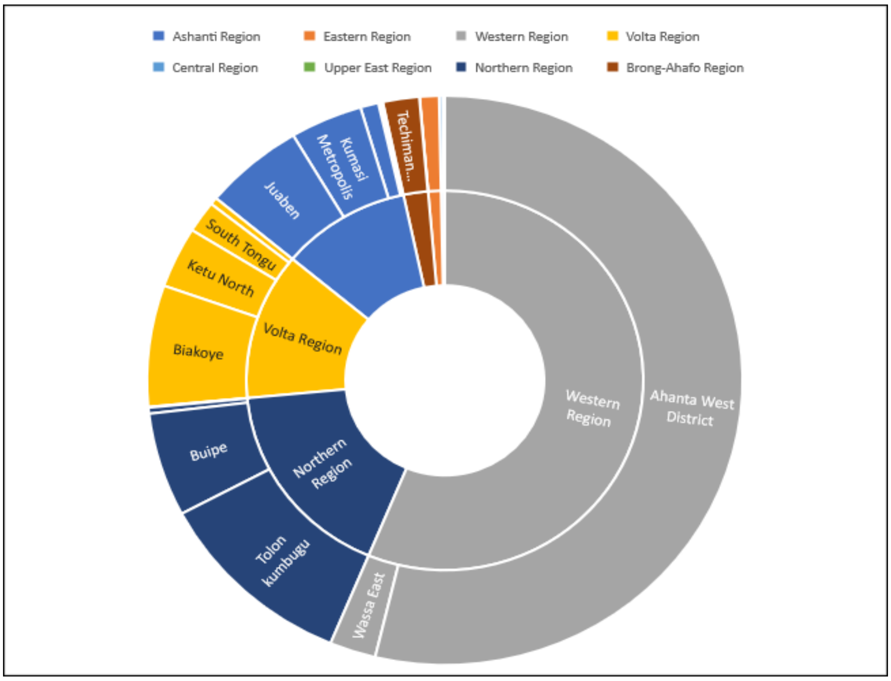

Fig. 1 Agro-process Residue Potential in the Various Regions and Districts

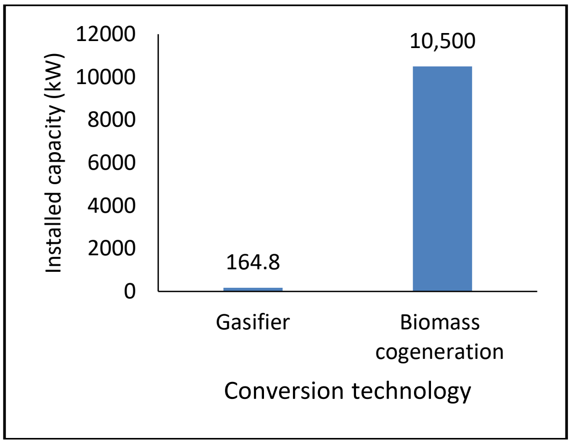

Fig. 2 Installed Conversion Technologies for Crop Residues in Ghana

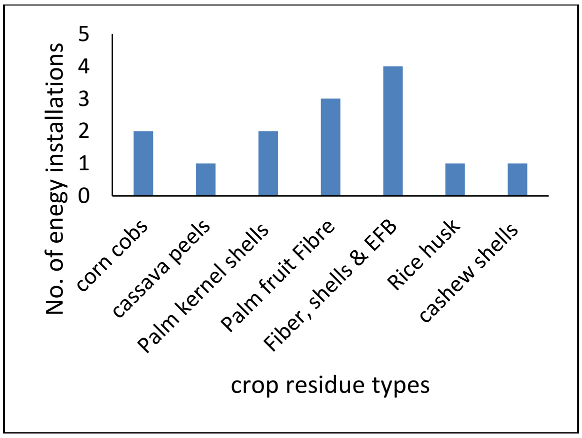

Fig. 3 Crop Residues Types in Use for the Conversion Technologies

Also, the installed capacity of Ghana Oil Palm Development Company Limited (GOPDC) is 4 MW but the plant currently generates 2.5 MW due to insufficient feedstocks. Similar situation has also been reported in Juaben Oil Mill Limited (Anon., 2016b). This can be addressed by purchasing residues from small- and medium-scale oil palm processors. Unused surplus electricity generated by these plants can be supplied to nearby communities thereby decreasing the overall burden on national grid electricity and generating other revenue stream for these companies. Other technical challenges that have been identified is lack of tailor-made technology to suit locally available residues. Imported technologies are often not able to function optimally, particularly gasifiers. Gasifier designs are fuel specific (Belonio, 2005). A typical example is the 24.8 kWe Papasi downdraft gasifier plant. Technical difficulties were encountered almost immediately after commissioning. It was reported that, the blower designed to help ignition and sustain the gas flow from the reactor to the engine were sized for different feedstock and could not generate enough air pressure through the palm kernel shell feedstock. This resulted in the damage of the feedstock feed auger. The main blower therefore broken down and had to be replaced. High tar and particulate matter production were observed due to the inability of the fan to draw enough air through the system resulting in sub-optimal reactor temperature. Similar situation has also been observed in gasifiers across SSA countries. The total operating hours of the gasifier since its installation in 2017 has been reported to be 56.3 hours (Owen and Ripken, 2017).

Another technical challenge identified is the inconsistent supply of feedstocks. This was identified to be a challenge for the 120 kWe downdraft gasifier plant in Asueyi in the Brong-Ahafo region of Ghana. The facility comes with an automated roasting system for gari production. The gasifier engine system consists of a downdraft gasifier, gas engine, backup generator, air generator along with a gas cleaning and cooling system. The gasifier is used for producing ultra clean gas for electricity and heat generation from the cassava processing waste. The main challenge with this facility is lack of sustainable feedstock (Anon., 2016b). This problem might have happened due to lack of sustainable residue assessment. Sustainable feedstock assessment might not have been done prior to the establishment of the plant and therefore sizing of the plant might have been based on theoretical residues assessments or technical but without using the correct RPR or the recoverability ratios. A study in the same community established that about 30 % of cassava peels generated annually are used to feed animals (Kemausuor *et al*., 2015b). Therefore, residue assessments that do not take into consideration these factors may oversize the power plant. Other available feedstocks such as cashew shells, maize cobs, rice husk (Addo *et al*., 2014) in the region can be exploited as feedstock for the plant taking into consideration pre-processing (compaction) to increase feedstock bulk density to reduce transportation costs per unit weight.

4 Conclusions and Recommendations

The outcome of the study revealed that, the level of crop residue assessment in Ghana is on theoretical and technical bases, employing either field survey or statistical modelling methods. There was wide difference between quantities of residues reported, mainly as a result of the differences in the methods of assessment, crop production figures, Residue to Product (RPR), and recoverability ratios. The Northern, Brong Ahafo, and Eastern regions have the highest potential in terms of total residues. The major crop residue types which were identified to be underutilised and therefore available for energy generation include: rice husk, cassava peels, and oil palm residues. Clustered small, medium, large-scale, and irrigated farms offer the largest opportunity aside agro-processors for sustainable and economically viable option for energy generation from crop residues. Overall, fourteen biomass energy installations using thermochemical conversion technologies were also identified, consisting of six biomass powered cogeneration plants, three gasifiers, four biomass boilers, and one hybrid solar biomass dryer. These plants have a total installed capacity of 10.7 MW with the large-scale palm oil processing industries contributing 10.5 MW. The major challenges identified for these installations were: unsustainable biomass supply, lack of tailor-made technology to suit locally available residues and inability of conversion technology to utilise all available residues.

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