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Geographical and economic assessment of feedstock availability for biomass gasification in Burkina Faso

Fanta Barry [a,c,*], Marie Sawadogo [a], Igor W.K. Ouédraogo [a], Maïmouna Traoré/Bologo [b], Thomas Dogot [c]

[a] Laboratoire Energies Renouvelables et Efficacité Energétique (LabEREE), Institut International d'Ingénierie de l'Eau et de l'Environnement (2iE), 01 BP 594 Ouagadougou 01, Burkina Faso

[b] Laboratoire Eaux Hydrosystèmes et Agriculture (LEHSA), Institut International d'Ingénierie de l'Eau et de l'Environnement (2iE), 01 BP 594 Ouagadougou 01, Burkina Faso

[c] Laboratoire d'Economie et Développement rural, Gembloux Agro Bio-Tech, University of Liège, Belgium

A R T I C L E I N F O

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A B S T R A C T

The crop production of Burkina Faso generates a large amount of residues that can be used for energy production. In the high crops production zone, people face low access to energy for household use and productive activities. Due to the widespread inefficient production and use of traditional energy sources, technologies as gasification have been implemented in rural areas for productive activities. One of the issues of implementing gasification in this country is the securing of biomass supply. This paper aims at assessing the availability of residues that could be used for gasification. Three levels of potential for plant and agro-industrial residues are estimated based on product-to-residue ratios and crop production. The results show that the theoretical agricultural residue pool is about 8 million tonnes. Sustainable recovery rates have been considered to protect soil fertility, human and animal consumption. Only cotton stalks and rice husks are recoverable at 75% and 20%. The mobilizable potential for bioenergy is 723,260 tonnes of cotton stalks and 6,497 tonnes of rice husks. These residues have an energy potential of 44,638 toe and 253 toe, respectively. The agricultural residues can therefore contribute sustainably to satisfy the bioenergy needs of the country's agro-industrial sector.

1. Introduction

Burkina Faso has a low rate of access to energy. This rate was 1.21% in rural areas in 2010 compared to 46% in urban areas due to the high cost of fossil fuels [1]. Households depend heavily on fuelwood and charcoal. This intense anthropic pressure leads to a perpetual decrease of forests [2]. The forests have been reduced from 11.4 million hectares in 2010 to 3.9 million hectares in 2017, an average reduction of about 66% [3]. Thus, alternative solutions must be found for energy production.

Energy-related CO_2 emissions increased by 6% from 33 Gt in 2015 to 35 Gt in 2050 according to current and planned policies [4]. Emissions must decrease to 9.7 Gt in 2050 to be compatible with the 2°Celsius objective of the Paris Agreement. The share of renewable energy in the total primary energy supply would increase from 14% in 2015 to 63% in 2050 [5]. Sustainable renewable energy sources do not include the traditional use of biomass for cooking and heating, which impact human health and the environment [6]. The use of modern solid bioenergy increases by an average of about 3% per year through 2050. In industry, where demand reaches 20 EJ in 2050, solid bioenergy provides high-temperature heat and can be cofired with agricultural residues to reduce emissions. Thereby, agricultural residues conversion will require new technologies. Biomass gasification is being recognized as a promising technology for the sustainable use of bioenergy [7,8]. This energy conversion process involves a cluster of complex chemical reactions in which large organic molecules are transformed into carbon monoxide, methane and hydrogen, and other flammable gases [9,10].

Gasification technologies have been used in Burkina Faso to produce heat and electricity, but they have failed [11]. Several studies have analyzed the reasons for the failure of these technologies [11,12]. For

* Corresponding author at: Laboratoire Energies Renouvelables et Efficacité Energétique (LabEREE), Institut International d'Ingénierie de l'Eau et de l'Environnement (2iE), 01 BP 594 Ouagadougou 01, Burkina Faso.

E-mail addresses: fbarry099@gmail.com, fanta.barry@2ie-edu.org (F. Barry), marie.sawadogo@2ie-edu.org (M. Sawadogo), igor.ouedraogo@2ie-edu.org (I.W.K. Ouédraogo), maimouna.bologo@2ie-edu.org (M. Traoré/Bologo), Thomas.Dogot@uliege.be (T. Dogot).

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some authors, the application of biomass gasification faces technical barriers such as gasification reaction temperature, and biomass moisture content [13,14]. In addition, the implementation of this technology has faced other extrinsic obstacles such as the planning problem and the level of knowledge of the gasification technology [13]. The technology cost remains unaffordable for African countries [15,16]. Also, a small subsidy fails to bridge the gap between financial assistance and the production cost, leaving projects short of funds [17]. In the context of Burkina Faso, one of the key barriers to the deployment of gasification technology is the issue with the availability and accessibility of biomass [18]. The country's agro-industry mobilizes rice husks and cashew nuts to generate heat, electricity, and steam [19,20]. However, there is lack of extensive investigations into the availability of feedstock for energy production in the country.

The availability of residual agricultural biomass is highly dependent on climatic hazards and competitive uses [21]. Due to seasonality, agricultural by-products must be harvested and then stored. In some cases, these products must be destroyed due to the risk of pest infestation. Crop residues have various uses. For example, maize, sorghum, and millet residues are often fodder or fuel for household needs. This situation leads to the relative availability of the raw material and very high storage costs. The assessment of the available and accessible quantities of agricultural residues becomes a central issue in energy recovery. Indeed, securing a sustainable biomass supply is critical for developing bioenergy and biomass-based products. This paper discusses biomass estimates for gasification energy needs. The specifics objectives are i) to estimate the quantity of residues produced at the national and regional level using statistical information on agricultural production and residue/product ratios obtained from the literature; ii) to estimate the sustainable biomass available for energy production taking into account several factors, including soil conservation, animal feed; iii) to determine the potential energy that can be generated from agricultural residues; iv) to develop spatial distribution maps of mobilizable agricultural residues throughout the country, and to identify major residue producing localities, and v) to analyze the cost of syngas production in areas with high mobilizable residue production to guide future entrepreneurial decisions.

2. Methodology

2.1. Study area

Burkina Faso is located in the area of the Niger River loop, between 9°20′ and 15°05′ North latitude, 5°20′ West longitude and 2°03′ East longitude [22]. Therefore, Burkina Faso is a landlocked country dependent on importing fossil fuels to satisfy national energy demand. Biomass, consisting of wood, charcoal, agricultural and agro-industrial residues, is the main energy source for about 90% of Burkina Faso's households. The wood deficit linked to the heavy deforestation of nearly 105,500 ha of forest per year [23] and the evolution of regulations on waste recovery has made it possible to develop technologies to obtain gas, with the installation of more than 3,000 biodigesters between 2010 and 2013, and fuel from biomass. The biofuel potential was significant, with an estimated area of over 80,000 ha in 2012 for oil production of 2.6 million liters.

The strength of the country's bioenergy programs currently lies in the agricultural sector. Most of the working population (~80%) depends on agriculture for their livelihood. In 2017, employment in the agricultural's sector was about 48.9%. In 2017–2018, agriculture contributed nearly 28.7% to the country's gross domestic product. Despite the immense contributions of the agricultural sector to the economy, it suffers from poor mechanization, declining fertility of soils, and climatic hazards linked to poor spatial and temporal rainfall distribution.

The main crops that are cultivated in Burkina Faso are millet, sorghum, maize, groundnuts, rice, cowpea, voandzou, yams, cotton, etc. Annual sown land occupies about 13% of the country's area. Rangelands represent about 60% of the national territory. Fig. 1 gives an overview of the evolution of crops production in Burkina Faso since 2015 [24].

These crops provide a large amount of residues. However, these resources are not exploited efficiently. There are also no specific data on the real potential for energy recovery, including alternative uses.

2.2. Data source and collection

For this study, data have been collected on the amount of agricultural and agro-industrial residues. The main data source is related to annual production rates and agricultural areas, derived from statistical data from the National Institute of Statistics and Demography of Burkina Faso. As most the agricultural produce is destined for both the local markets and the processing industries such as rice and oil mills, the average quantities processed in the agro-industries were quantified from the same data source. In addition, data on the endogenous use of biomass was collected from members of rice processors unions, groups of agricultural producers, technical agents for agriculture and cotton correspondence. The information was collected in areas of low production (Plateau central and Centre sud) and high agricultural production (Hauts-Bassins and Boucle du Mouhoun) (Table 1). The proportions of endogenous use of agricultural residues were compared to the Food and Agriculture Organisation (FAO) standards and the literature.

Given the unavailability of commercial technologies in Burkina Faso, data on equipment and installation costs were obtained from Indian suppliers. Raw material prices, labor and biomass transport costs are taken from interviews with experts. An extensive literature review was also carried out to identify appropriate parameters and methods for assessing the energy potential of biomass production.

2.3. Key parameters for crop residues availability

The energy potential of crop residue is estimated considering many parameters that will be highlighted here. It considers the gross residue potential derived from the general statistical data on annual crop production. The residues that must be left on the soil surface to enhance and protect soil quality are also considered. Another parameter influencing crop availability for energy production is the competition between food, fuel, and feed in the use of residues. Moreover, the influence of the production cost on the availability of biomass are studied.

The evaluation of biomass quantities consisted of three possible levels: theoretical, mobilizable, and bioenergy [25,26,27] (Fig. 2).

2.3.1. Theoretical potential quantity of biomass

The theoretical quantity of biomass depends on the Residue-to-Product Ratio (RPR) related to the generated biomass residue to the total produced biomass.

The theoretical potential biomass (QT_i) is estimated from the average production per crop and the ratio between the number of residues and the amount of raw product before processing *(Eq1)*.

$$QT_i = P_i{*}RPR_i \quad (1)$$

where QT_i(tonnes) is the theoretical potential quantity of residue from crop *i*,

P_i (tonnes) refers to the annual production of the crop *i,* and RPR_i is the Residue-to-Product Ratio of the crop *i*.

A robust estimate of biomass potential is based on a ratio value appropriate to the study area [21]. RPR depends on several factors, including local soil and climatic conditions, differences in farming practices such as the rates and types of fertilizer applied and the height of stem cutting during harvest, the various categories used, and the crop production values. Thus, this paper favored data sources specific to West Africa, particularly for areas with a Sahelian climate. However, there is little literature on RPR in these areas. The limited research does not cover all crops, making it challenging to synthesize data by speculation

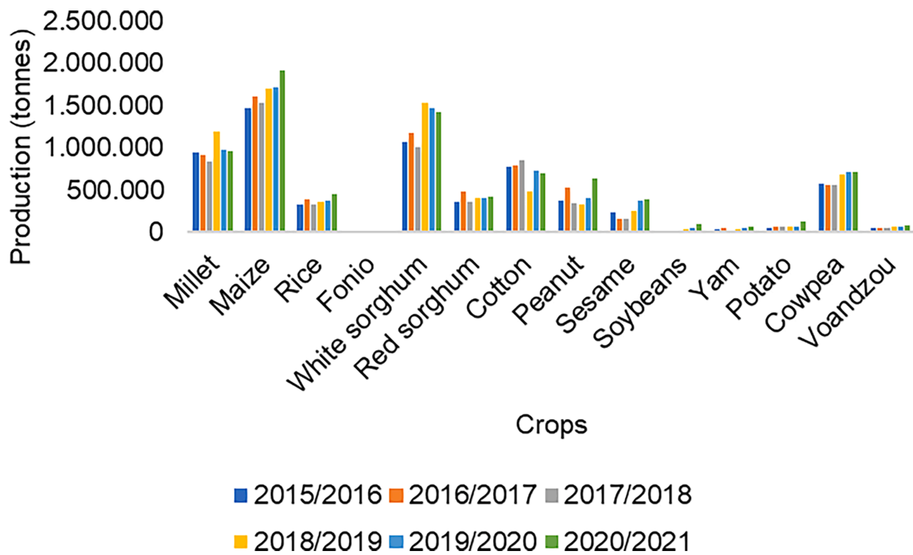

Fig. 1. Evolution of crop production in Burkina Faso [24].

Table 1
Information collection sample.

Area zone	Transformers of rice	Technical agents of agriculture / Cotton Correspondence	Producers
Bama (Hauts-Bassins)	11	1	5
Dedougou (Boucle du Mouhoun)	0	1	10
Kombissiri (Centre sud)	0	1	15
Mogtedo (Plateau central)	15	1	7
Total	**26**	**4**	**37**

and country. Table 2 gives the RPRs found in the literature.

The table above shows that the RPR of maize stalks, maize cobs, cotton stalks, and sorghum stalks are wildly divergent in the literature. An estimate made in Burkina Faso from maize and sorghum yield data with varying fertilizer doses yielded ratios of 0.9 and 0.5. For cotton, this ratio is about 1.8 for the 2018–2019 season in the Koumbia area of Burkina Faso. For rice, the ratio is 0.21, as in many studies. So, RPR values would vary for different farms and regions, as mentioned above. Thus, an average of the varying RPR values was considered for the values of very disparate ratios. The least diverging values were used for the calculation of residue quantities.

2.3.2. *Competitive use of crop residues and mobilizable potential*

Biomass has various uses. It is either burned in the field, buried to improve or maintain soil fertility, protection against erosion and used for animal feed and bedding, or domestic heating and cooking [36]. Residues used for other purposes are calculated based on the defined percentage of total residues produced. According FAO, the amount of residue left in the field is calculated as a product of the total sum of residues produced per year and the user-defined percentage of residues left in the area or the default value provided by the residue assessment tool. This default value for residue use is 25% if the residue is generated or collected in the field and 0% if the location is at the processing plant. A recoverability fraction of 10% to 25% of the total available residues has been assumed in previous studies [37] for energy purposes. Kemausuor and coll. [29] consider 10%, 25%, and 40% availability of residues representing low, medium, and high.

The available or mobilizable potential corresponds to the fraction of theoretical potential that is possible to extract, taking into account access and appropriation rights, without modifying the current uses of the various actors producing this biomass. The mobilizable quantity of biomass (QM_i) is calculated by applying the following *Eq (2)*.

$$QM_i = QT_i{}^*\alpha_i \tag{2}$$

where QM_i(tonnes) is the mobilizable potential quantity of residue from the crop i,

QT_i(tonnes), the theoretical potential amount of residue from crop i and,

α_i, the recoverability fraction based on several assumptions of residue use.

2.3.3. *Energy potential calculation*

The available energy potential corresponds to the calorific energy contained in the biomass, considering its dry matter content and lower heating value (LHV). The moisture content of the biomass can affect the quality of the gas in terms of calorific value and the effectiveness of the gasification process [38]. Biomass with high moisture content produces gas with a low calorific value. With a moisture content of more than 30%, biomass absorbs more heat during its drying process. The heat required for the complete pyrolysis process is insufficient. The calorific value of the gas is thus reduced during gasification [39].

The LHV of biomass also creates many barriers during its conversion by gasification. Most agricultural residues have an LHV between 16 and 20 MJ/kg [40,41].

The quantity of energy produced per year (E) is calculated by the following *Eq (3)*.

$$E = QM_i{}^*LHV_i{}^*\eta_{global} \tag{3}$$

where E (toe) is the annual gross energy potential of bioenergy feedstock type,

LHV_i(MJ/kg), the Lower Heating Value of the residue of the crop i and,

η_{global} is overall system performance depending on the biomass moisture content.

2.3.4. *Calculation of the accessibility of the mobilizable residues*

The calculation of the accessibility of the mobilizable residues by applying the gasification requires a cost price analysis of the gas from the mobilization of the biomass to the exit of the gasifier. The cost price

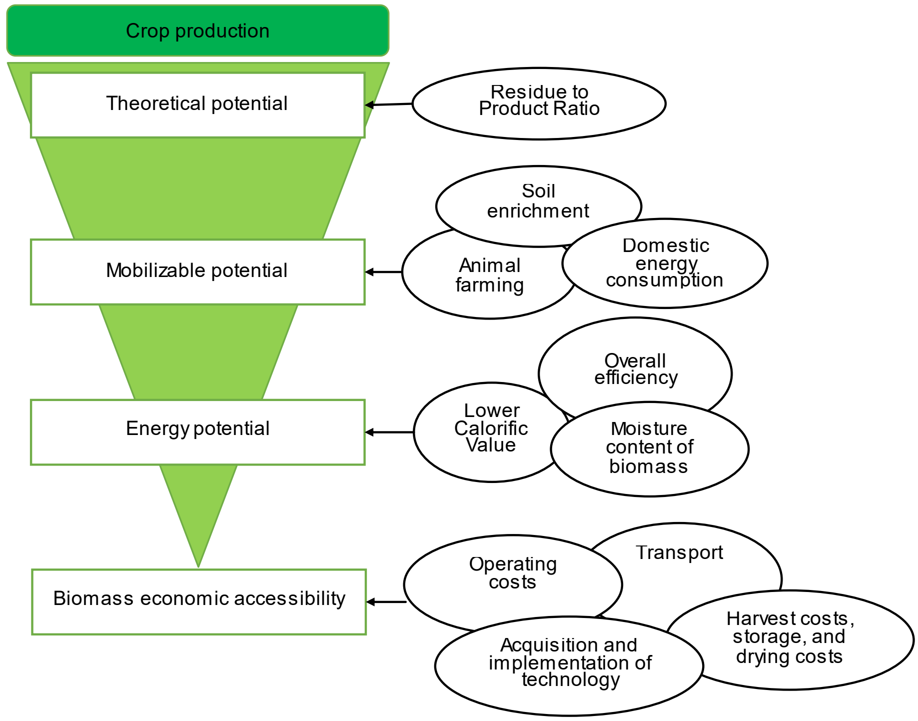

Fig. 2. Levels of assessment of the availability of agricultural biomass.

Table 2
Average residue to product ratio applied to each residue studied.

Agricultural Residues	Residue to Product Ratios	Source	Average Ratio Used
Rice husks	0.21	[28,29,30]	0.21
Maize stalks	0.9–1.5	[31,32]	1.2
Maize cobs	0.5–0.8	[33,34]	0.65
Cotton stalks	1.5–2.5	[28,34]	2
Peanut shells	0.4	[35]	0.4
Sorghum stalks	2.0 – 2.5	[28,34]	2.25

was determined from the direct and indirect costs by applying the following *Eq (4)*.

$$Cost\ price = \frac{\Sigma\ Indirect\ \text{and}\ directcosts}{Quantities\ produced} \tag{4}$$

2.3.4.1. Transport costs. The cost of transport was estimated per unit and distance. The hypothesis is based on the use of a 20 tonnes truck (75 m^3 volume capacity). This kind of truck transports agricultural products at 1.5 €/km/20tonnes. For the transport distance, the gasification plant that has been considered is located in Bama area in the Hauts-Bassins [18]. The maximum average distance of 152 km covers the regions with high residue production by Bama-Orodara (106.5 km) and Bama-Dedougou (197.4 km) axes. This distance corresponds to the threshold accepted in the literature for economically viable residue collection, with distances ranging from 80 to 161 km [42,43].

2.3.4.2. The cost associated with agricultural residues. The costs associated with agricultural residues consisted of harvest costs, storage, and drying costs [44]. These components were supposed to be constant per area and invariant across crops. Harvesting costs were assumed to be equivalent to 15 €/ha/2tonnes based on field information. Storage and drying costs were estimated at 15 €/tonne.

2.3.4.3. Operating costs. The operating costs of a gasification plant are calculated on an annual basis and generally consist of the costs of maintenance, workforce, and the purchase of biomass, as well as the replacement of spare parts. Maintenance and repair costs include all expenses related to the maintenance of the equipment. These costs are often assumed to be equivalent to a flat rate of 6% of the initial investment cost, according to experts who have worked on gasification projects in Burkina Faso [45].

The operating staff of a gasification unit includes an engineer in charge of coordinating the operation of the equipment. He is assisted by a qualified mechanical technician and two semi-skilled or unskilled laborers in charge of preparing, handling, and feeding the biomass to the gasifier inlet. The monthly salary is 460 € for the engineer, 250 € for the mechanical technician, and 150 € each for the two laborers. This amounts to an annual salary of 12,120 €. Adding 25% for social security contributions, the total annual operating cost is 15,150 €.

2.3.4.4. Investment costs. The initial investment consists of the cost of the gasifier and gas cleaning, the cost of transport, insurance, and installation. The market for gasifier technologies does not yet exist in African countries. This makes it difficult to access accurate information on investment costs. The gasifiers used are fixed beds with 44 kW installed electrical capacity whose prices vary from 20,960 € to 746,177 € according to the Indian manufacturer ANKUR. They are supposed to produce syngas for heat. These types of gasifiers consume 2 kg per hour. This brings the consumption to 200 kg per day, or about 48,000 kg per year (48 tonnes per year) when supposing, operating time of at least 10 h per day for 240 days in the year. For the implementation of the equipment, a percentage of the total investment cost of the system can be applied according to the installed power: 15% if the power is less than 20 kW, 10% if it is between 20 and 100 kW, and 8% if it is more than 100 kW. The lifetime of the equipment is assumed to be 10 years. The depreciation of the equipment is considered constant in this paper. The cost of installing and transporting the equipment from India to the location of the power plant in Burkina Faso averages 5,000 €.

2.3.5. Spatial distribution of biomass

The quantification of biomass has been established at the level of administrative regions. The exact geographical location of agricultural areas could better specify the service area for the supply of gasifiable residues. So, ArcGIS 10.6 software was used to create spatial distribution maps based on biomass density derived from the total amount of mobilizable biomass and the area covered by each biomass type in Burkina Faso. This mapping showed the spatial distribution of residues and identified the localities generating the largest volumes of agricultural residues.

3. Results and discussion

3.1. Evolution of agricultural residues

The evolution of the volume of agricultural residues in Burkina Faso depends on the areas of crops, crops varieties, and rainfall [46]. Residues available from cereals include maize and millet stalks, maize and rice hulls, rice and sorghum straw, and maize cobs. Maize and cotton are produced throughout the great west and almost everywhere in the country's other regions. These crops are produced in relatively large quantities. Other crops like sorghum and groundnuts provide less residue as they are produced in very few areas. As mentioned in the methodology, the theoretical potential of residue was calculated using residue to product ratios (RPRs) and crop production data obtained from the statistic database and literature. Fig. 3 shows the status of theoretically available residues between 2007 and 2018.

The figure indicates a slight trend of increasing residues between 2007 and 2011 and a pronounced increase between 2012 and 2018. This can be explained by the fact that the amount of residues varies exponentially with the amount of grain harvested, which is sensitive to rainfall and the producer's attitude towards recommended agricultural practices. For example, applying technology packages such as the combination of stone cordon, zaï, NPK, and urea improved sorghum grain yields. Grain yield gains between farmers' endogenous practice and technology packages ranged from 5.66% to 44.45% in 2018 and from 25.15% to 53.80% in 2019 [47]. The combination of micro-dosing of fertilizer, the use of improved varieties and organic manure, the disk seeder, water, and soil conservation techniques, and producers' access to fertilizer subsidies have been shown to have a significant impact on millet and sorghum yield [48,49]. The more favorable these conditions are, the more abundant the grain and residue harvests. However, a more detailed analysis shows that cotton stalks have not significantly increased. They remained at a low level after the 2009 drop until 2014, when they peaked slightly. This period of decline corresponds to the controversial use of genetically modified *Bt* cotton [50]. There was also no increase in peanut hulls and rice husk. While corn stalks, cotton stalks, corn cobs, and peanut hulls had observable increases between 2012 and 2018, sorghum stalks oscillated with significant declines in 2011 and 2016. This can be explained by the fact that sorghum is generally grown in the less watered part of the country. Also, long pockets of dryness can be found at the beginning and end of the season [51].

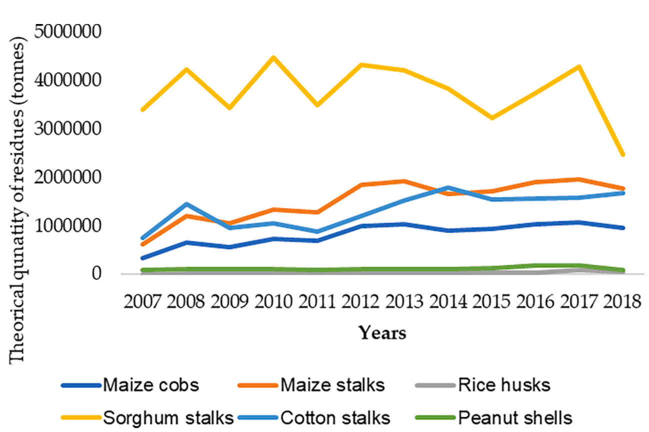

Fig. 3. Evolution of the quantities of agricultural residues at the national level.

3.2. Theoretical availability of agricultural residues

The theoretical deposit of all agricultural residues is around 8 million tonnes in 2018 nationally. The quantity of available residues includes 51% sorghum stalks, 37% maize stalks and cobs, 11% cotton stalks, and a small proportion of peanut hulls and rice husks (Fig. 4).

The analysis at the regional level shows that the regions of high agricultural production record the most residues with proportions of 16.05% for the Boucle du Mouhoun region and 15.47% for that of the Hauts-Bassins as presented in Table 3.

3.3. Competitive use of residues

The sustainable potential of residues produced for energy purposes depends on their density and competitive uses in the region. From interviews with producers, there is strong competition in the use of residues, particularly sorghum stalks, maize stalks, maize cobs, and peanut shells (Table 4).

The table shows that agricultural residues are generally used for livestock (animal feed and poultry litter), soil fertilization (direct amendment and composting), and domestic use (construction of huts, manufacture of potash, energy for domestic consumption).

Residues are often stored as animal feed during the dry season. However, this use is very low in areas with a high potential for herbaceous and woody fodder. The use of millet and sorghum stalks for fire is low in relatively forested areas with large quantities of fuelwood. In contrast, the supply of fuelwood is often limited, as in the case of Bama. Rice husks are then used as a substitute. These competing uses could reduce the amount of biomass available for bioenergy in the case of results obtained from similar studies in Bolivia [21]. Only cotton stalks are not used. But they have a low density and therefore require a significant investment in logistics and harvesting. Further analysis will focus on rice husks and cotton stalks.

3.4. Mobilizable and energy potential of residues

The mobilizable potential of agricultural residues for bioenergy in the Burkina Faso context consists of crop residues such as cotton stalks and agro-industrial residues, mainly rice hulls. Table 5 summarizes the potential of rice hulls and cotton stalks for 2018 by region.

The table indicates a relatively low mobilizable potential of rice husks of around 6,497 tonnes for the year 2018. The low level of residues could be linked to the fact that rice is the 4th most important cereal crop in Burkina Faso, as reported by Netherlands Development Organization (SNV) [52]. Moreover, this estimated potential is obtained after processing. However, it contains an energy potential of 253 toe at the national level. At the regional level, the highest potentials are recorded in 6 of the country's 13 administrative regions.

Cotton stalks constitute more than half of the mobilizable potential in agricultural residues at the national level. This mobilizable potential is about 723,260 tonnes in 2018. It is equivalent to an energy potential of 44,638 toe. At the regional level, the Boucle du Mouhoun and Hauts-Bassins regions have the highest potential with quantities of 7,806.52 and 13,324.82 toe respectively.

The two mobilizable residues (cotton stalks and rice husks) have an energy potential that could cover about 50% of Burkina Faso's energy needs (90,525 toe for the year 2018). This implies that these residues could contribute significantly to the sustainable satisfaction of the future bioenergy needs of the country's agro-industrial sector. The residues are highly concentrated in the western part of Burkina Faso, the area most suitable for agriculture. This constitutes a potential for the implementation of a gasification plant (Fig. 5).

The figure shows that the low densities of cotton stalks are observed

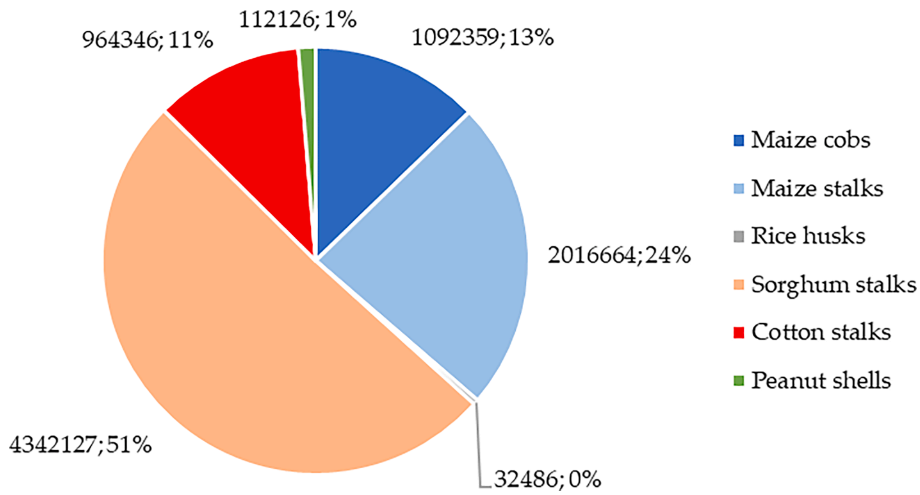

Fig. 4. Size of the national theoretical deposit of agricultural residues in 2018.

Table 3
Theoretical availability and proportion of agricultural residues in 2018 by region.

Region	Theoretical availability (tonnes)							Proportion of residues (%)
	Maize cobs	Maize stalks	Rice husks	Sorghum stalks	Cotton stalks	Peanut shells	Total	
Centre	13 183	4 056	620	59 430	–	22 667	99 957	1.19
Plateau central	30 974	9 531	720	276 114	7 451	51 360	376 149	4.47
Centre nord	8 208	2 526	4	412 831	421	115 884	539 875	6.41
Centre ouest	132 218	40 682	1 235	523 965	58 536	251 135	1 007 771	11.97
Centre sud	63 576	19 562	24 89	196 908	51 305	127 441	461 282	5.48
Sahel	3 690	1 135	6	220 636	–	28 595	254 061	3.02
Boucle du Mouhoun	**130 864**	**40 266**	**8 279**	**826 747**	**168 650**	**175 708**	**1 350 514**	**16.05**
Est	63 055	19 402	5 205	542 749	100 318	195 730	926 459	11.01
Centre est	101 769	31 314	3 679	251 099	92 833	169 609	650 303	7.73
Nord	6726	2 069	143	339 706	–	179 834	528 478	6.28
Sud-ouest	103 225	31 762	536	226 989	108 190	60 299	531 000	6.31
Hauts-Bassins	**312 088**	**96 027**	**6 990**	**419 262**	**287 866**	**179 722**	**1 301 954**	**15.47**
Cascades	122 783	37 779	2 581	45 693	88 777	90 931	388 544	4.62
Burkina Faso	**1 092 359**	**336 111**	**3 2486**	**4342 127**	**964 346**	**1 648 917**	**841 6347**	**100**

Table 4
Competitive use of Burkina Faso agricultural residues.

Agricultural residues	Household energy	Animal fodder	Poultry litter	Left in the field	Compost	Proportion of use (%)
Rice husks	X	–	X	–	–	80
Maize stalks	X	X	–	X	X	100
Maize cobs	X	–	–	–	X	100
Sorghum stalks	X	X	–	X	X	100
Cotton stalks	–	–	–	X	–	0
Peanut shells	X	X	X	–	X	100

(X)*Used residues.*

in the provinces of seven regions such as Sahel, Plateau central, Centre, Centre nord, Centre ouest, Centre sud, and Cascades. The most extensive stock is recorded in localities such as Hauts-Bassins and Boucle du Mouhoun with a density of at least 100 tonnes/km^2. This area of high production could be more suitable for a possible installation of a gasifier with a capacity of 1 MW. However, cotton stalks are characterized by their low density in the fields. This could increase harvesting and transport costs and consequently energy production costs.

3.5. Accessibility of mobilizable residues

The cost analysis provides two options in having access to the residues. They are 1) using local gasification technology, and 2) using imported gasification technology (Table 6). The cost price is from the division of the investment and operating costs by the quantity of energy that can be produced.

The table shows that the cost price varies according to the type of residue and the origin of the conversion technology. Indeed, the cost price of gas from rice husks is slightly higher than that from cotton stalks. This is due to the specific characteristics such as the lower heating value and moisture content of each residue that can affect the gasification process. It is in accordance with the results obtained in evaluating oil palm as an energy source in Malaysia [38]. Furthermore, the analysis based on the origin of the technology shows that with a locally manufactured technology, the cost price is relatively low, i.e. 0.09 €/kWh of gas from rice husks compared to that obtained with the hypothesis applying an imported technology (0.10 €/kWh). The same result is observed for cotton stalks, i.e. respectively 0.07 and 0.09 €/kWh, when considering a local gasifier and an imported gasifier. This difference in cost price is due to the expenses related to the operation and acquisition of the gasifier.

As the purchasing cost is the highest item, it could be reduced by

Table 5
Mobilizable and energy potential of agricultural residues in 2018 by region.

Regions	Rice husks Mobilizable potential (tonnes)	Energy potential (toe)	Cotton stalks Mobilizable potential (tonnes)	Energy potential (toe)
Centre	124	4.82	–	–
Plateau central	144	5.60	5,588	344.89
Centre nord	1	0.03	316	19.51
Centre ouest	247	9.61	43,902	2,709.52
Centre sud	498	19.37	38,479	2,374.83
Sahel	1	0.04	–	–
Boucle du Mouhoun	**1,656**	**64.44**	**126,487**	**7,806.52**
Est	1,041	40.51	75,238	4,643.55
Centre est	736	28.63	69,625	4,297.09
Nord	29	1.11	–	–
Sud-ouest	107	4.17	81,142	5,007.91
Hauts-Bassins	**1,398**	**54.41**	**215,899**	**13,324.82**
Cascades	516	20.08	66,582	4,109.32
Burkina Faso	6,497	252.86	723,260	44,637.97

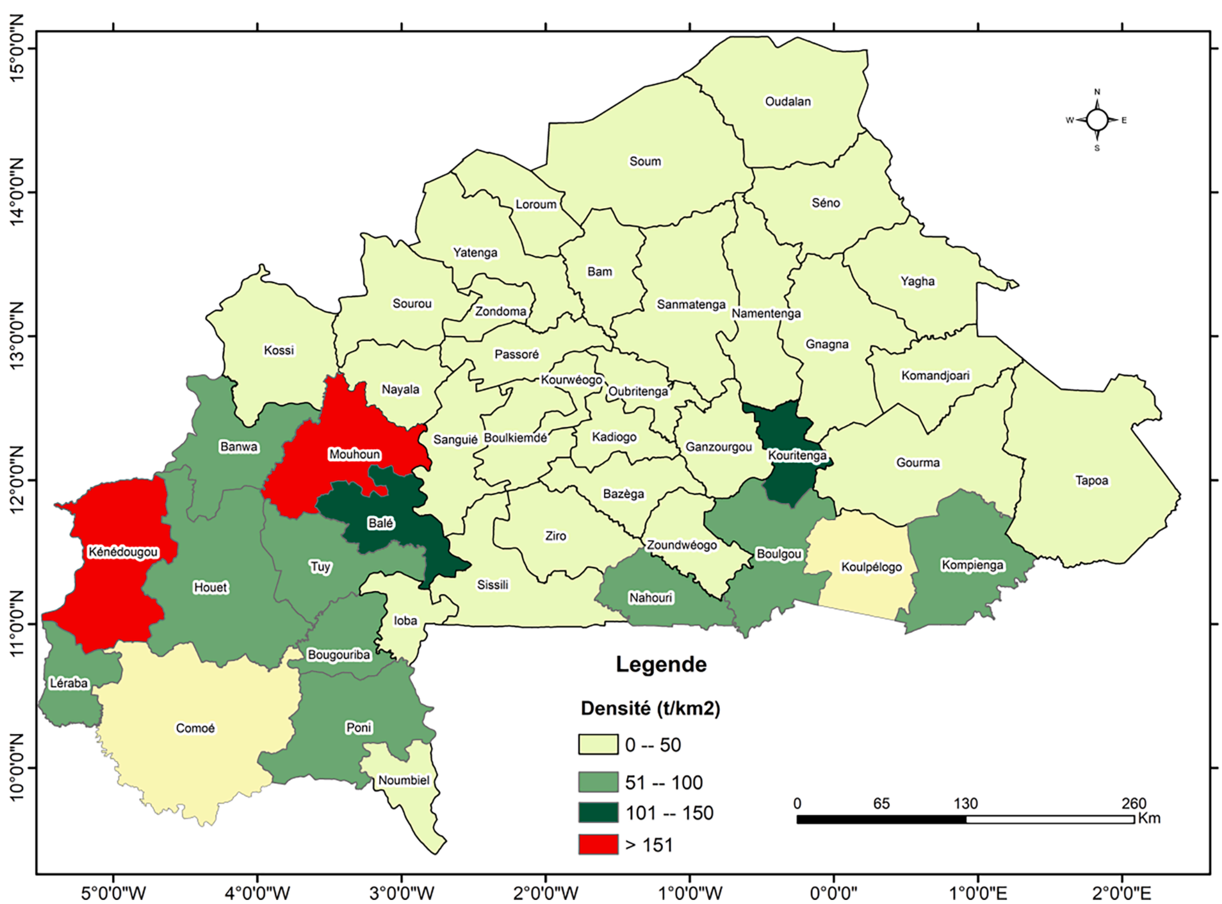

Fig. 5. Cotton stalk density of Burkina Faso provinces.

implementing and improving local technologies. To optimize the margin while maintaining a competitive price compared to the competition, which is the price of butane gas, an analysis based on the determination of the value of the subsidy was carried out (Table 7).

Given the results in Table 7, agricultural biomass is an ecologically viable source of energy, and its economic accessibility is attractive compared to butane gas. The subsidy proportion is around 50% regardless of the residue and the technology. As butane gas is imported, it can be an advantage for the country to promote the use of agricultural residues as a source of energy.

4. Conclusion

Burkina Faso, like any developing country, faces an energy deficit, especially in times of high demand, which seriously affects the country's economic growth. In addition to being exposed to severe environmental impacts, the government has to spend a large part of its revenues on importing energy from neighboring countries such as Côte d'Ivoire and Ghana [53]. The situation demands that the authorities make efforts to produce energy from local resources and tackle the energy crisis. In addition to solar energy, the country has a great potential for agricultural residues to help bridge the energy gap. This article provides the sustainable and accessible potential of agricultural residues that can be

Table 6
Cost price of the gas from mobilizable agricultural residues.

Item	Local technology		Imported technology	
	Value for rice husks	Value for cotton stalks	Value for rice husks	Value for cotton stalks
Fraction physically accessible by gasification (t/y)	48	48	48	48
Gasification efficiency	30%	30%	30%	30%
Potential energy (kWh)	194,400	252,000	194,400	252,000
Average collection distance (km)	0	152	0	152
Transport cost (€)	0	456	0	456
Harvest cost (€)	0	360	0	360
Storage and drying (€)	0	720	0	720
Annual depreciation cost of the technology (€)	2,096	2,096	2,096	2,096
Cost of technology transport, and implementation (€)	0	0	5,000	5,000
Operating costs (€/y)	15,150	15,150	15,150	15,150
Cost price (€/kWh)	**0.09**	**0.07**	**0.10**	**0.09**

Table 7
Comparison of the cost price of kWh of different energy sources according to subsidy and non-subsidy options.

Item	Without subsidy	With subsidy	Value of subsidy in existence or desired*	Proportion of subsidy desired (%)
Butane gas cost (€/kWh)	0.10	0.05	0.05	52.38
Local technology				
Cost from rice husks (€/kWh)	0.09	–	0.04	42.04
Cost from cotton stalks (€/kWh)	0.07	–	0.01	21.53
Imported technology				
Cost from rice husks (€/kWh)	0.10		0.05	48.99
Cost from cotton stalks (€/kWh)	0.09		0.04	43.33

*= The desired subsidy for a cost per kWh from agricultural residues at most equal to the cost per kWh of butane gas on the local market (with subsidy).

converted into energy through gasification.

The theoretical potential of agricultural residues amounts to about 8 million tonnes. The most available residues at the national level are from maize and sorghum cultivation. The planning of a gasification plant must consider the available resources and their competing uses. Competing uses, such as livestock feeding, soil fertilization, or household energy consumption have reduced the amount of biomass available for bioenergy. Only cotton stalks and part of the rice husks can be valorized. All crop residues such as maize stalks and cobs, sorghum stalks, groundnut husks are destined for other uses.

Large-scale use of these agricultural biomass resources could help improve the energy situation of agro-industries in Burkina Faso by reducing imported energy. However, decision-makers need to develop short and long term policies to produce more energy using indigenous biomass resources to reduce the energy crisis in the country.

The valorization of cotton stalks through gasification is seen as an opportunity to improve the income of small-scale cotton farmers, especially women and youth who are heavily involved in cotton cultivation.

A future study will analyze the optimal location of biomass energy conversion facilities. This study has identified the areas that generate the most agricultural residues. However, the site of a facility requires the analysis of social, environmental, and economic factors. Concerning support policies, there is a need for a policy to support the production of syngas as well as butane gas and to prohibit agricultural residues from being burnt in the field. In order to encourage agro-industrialists to use crop residues as an energy source, a subsidy policy for gasification must be developed. This subsidy should be higher than 40% irrespective of the type of residue. The origin of the gasification technology needs to be competitive with the cost of kWh from butane gas. Two significant recommendations emerge 1) either subsidize the acquisition of the conversion technology or 2) find locally available and accessible technologies for African countries.

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CRediT authorship contribution statement

Fanta Barry: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Marie Sawadogo:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **Igor W.K. Ouédraogo:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **Maiimouna Bologo Traoré:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. **Thomas Dogot:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

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

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