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ORIGINAL RESEARCH

Potentials of sustainable electricity production from sawdust by small-scale wood transformation units: a case study in Cameroon

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Abstract

Wood processing produces large volumes of residues which, when not properly managed, pose an environmental problem in the vicinity and beyond. These residues mainly constituted of sawdust and wood shavings, possess important energy potentials that are largely underexploited in Cameroon. In this work, we investigate the possibility that sawdust generated by wood transformation units (WTU) in Cameroon can be used sustainably to render them self-sufficient in terms of electricity demands through the production of syngas in a gasification process. Both qualitative and quantitative methods are used in the research. Initially, a questionnaire was employed to quantify the sawdust produced in the town of Yaounde, Cameroon. A major WTU "LFM_Sciérie" was selected to evaluate the feasibility of electricity generation from syngas produced by gasification of its wood waste. Proximate analysis of sawdust sampled from the LFM sawmill included moisture content $17.74 \pm 0.27\%$, ash content $3.91 \pm 1.54\%$, volatile matter $74.62 \pm 1.47\%$, and fixed carbon 3.73%. The gross calorific value of the sawdust sample was estimated to be 20.08 MJ/kg. The total quantity of sawdust produced in the Yaounde municipalities is 290 tons/week which translates to an energy potential of 713 GJ/week. Theoretical calculations and modelling using a thermodynamics software, Cycle-Tempo, indicate that the amount of sawdust generated at the LFM sawmill of about 7 tons/week, can conveniently satisfy its electricity demands of approximately 3.3 MW/week. Small-scale WTUs in Yaounde can be rendered energy-autonomous by the generation of electricity from syngas produced via a gasification process of its waste.

Keywords Syngas · Sawdust · Energy production · Wood transformation · Cameroon

Abbreviations

WTU	Wood transformation unit
LFM	La Forèstiere de Moloundou
ha	Hectares
RWE	Round wood equivalent
CV	Calorific value, MJ/kg
HHV	Higher heating value, MJ/kg
LHV	Lower heating value, MJ/m^3
GPS	Global positioning system
m	Mass, kg
V	Volume, m^3
$\eta_{electric}$	Electric efficiency
η_{gas}	Conversion efficiency, %
EP	Energy potential, kJ
P_{el}	Electrical power, kW
φ_m	Mass flow, kg/s
P	Pressure, bar
T	Temperature, °C
h	Enthalpy, kJ/kg

Introduction

The backbone of the development of every economy, both in the developed and developing world, is energy. Access to energy is still very limited to millions of local dwellers in Sub-Saharan Africa who still depend on traditional wood fuel for cooking [1]. The main sources of commercial energy in Cameroon, for example, are hydropower and fossil fuels [2]; the former is vulnerable to variations

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in rainfall [3] while the latter is subject to price volatility due to dependence on imported energy carriers [1, 4] and its use is associated with anthropogenic climate changes.

According to [5], rising energy prices, geopolitics, national security, and the impacts of greenhouse gas emissions on global climate changes, are driving large-scale efforts to implement biobased energy alternatives. In recent years considerable attention has been directed towards biomass as a sustainable energy resource with the potential to eliminate large amounts of greenhouse gases [6–8]. Bioenergy resources are spread over a wide variety of biomass, mostly involving crops grown to satisfy the ever-growing global energy demand. However, emphasis on these energy crops has sparked a clash of differing opinions between using land for food production and using land for energy production [9]. Nevertheless, several other options such as biomass residue from agricultural and forestry (wood) products have been considered. Bioenergy is critical not only because of environmental concerns but also because it provides a diversified energy mix, reduces over-dependence on imported fossil energy carriers, ensures the sustainable use of natural resources, and provides an opportunity for the revitalisation of rural economies [10].

Cameroon has the third-largest biomass potential in Sub-Saharan Africa [11] with a promising potential to fill in the void of the unsatisfied energy demand. Up to 40% of Cameroon’s total surface area is covered by forest representing about 22 million hectares (ha), 79% of which is exploitable for timber [12]. This has led to significant exploitation and development of the local wood industry, making Cameroon the sixth largest exporter of tropical woods worldwide, with an average of more than 1.5 million cubic metres of round wood equivalent (RWE) exports each year [13]. During processing, however, residue quantities estimated at 36% [13] are generated due to the low efficiency of the transformation industry (compared to other countries). Only a minor part of this residue is removed and utilised [7] as fuelwood for cooking purposes in household kitchens; a practice that is associated with undesirable side effects such as indoor pollution [5]. The rest is usually wasted and sometimes poses both environmental pollution as well as health threats [14, 15]. It has been documented that in Cameroon, wood-based waste is largely unexploited for energy purposes [4, 13, 16]. Moreover, the FAO [17] reported that “were all the residues resulting from forest operations in Cameroon to be used for electricity generation, the country would be able to produce five times its current demand”.

Information on the quantity of wood-based waste generated in Cameroon is quite scarce and the available literature depicts contrasting values. A survey by Nzotcha & Kenfack [13], of 34 facilities concluded that about 62% of raw logs fall as residues in various forms, while Mboumboue and Njomo [1], reported that Cameroon produced about 301 kilotons of sawdust and wood chips in 2009.

Sawdust, which is a type of wood residue, like most biomass, possesses the potential for energy production employing several known and mastered techniques, including biochemical and thermochemical processes [18, 19]. Biomass fuels, which include untreated biomass or biomass-derived gaseous, liquid, and solid fuels that have undergone mechanical, chemical, and/or biological processes can be used to produce different forms of energy or energy carriers (electricity, heat, solid, gaseous, and liquid fuels) [5]. The biofuel potential of residual wood waste (sawdust) is largely unexploited in Cameroon and consequently, this bioenergy resource regarded as waste is often disposed of unsustainably. In underdeveloped (rural) areas of Cameroon, wood-based residues are almost entirely used for domestic heating and cooking [1], animal fodder or fertiliser, while important quantities accumulated at sawmills are often just burnt or disposed of in nearby bushes as a strategy [14, 20]. Apart from a few trials at very low scales, Cameroon is not practicing any commercial production of biofuels [21].

The absence in Cameroon of a national bioenergy policy, which would serve as an umbrella for the exploitation of this untapped bioenergy resource and that would lead to wealth creation especially in rural areas, has contributed greatly to the misconception, mismanagement and neglect expressed towards sawdust and waste in general. Also, the lack of adequate data relative to the energy potential of local wood species [22] has been noted as a key hindrance to the development of bioenergy in Cameroon [4, 16]. Moreover, the scarcity of relevant information especially at a decentralised level has not encouraged rural development schemes to manage and harness this resource sustainably.

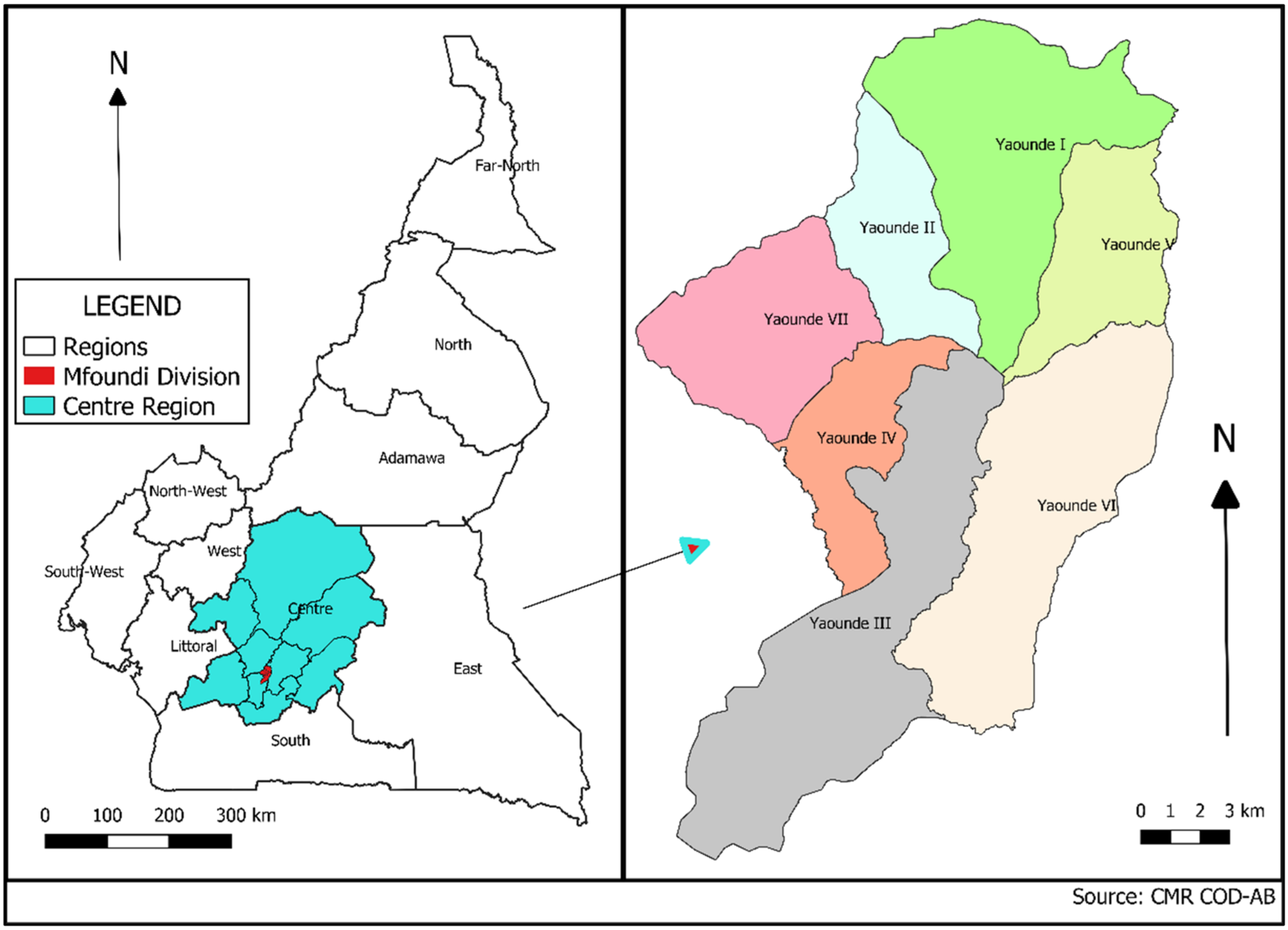
Renewable energies are fairly developed in the US, Brazil, and most European countries with processes being developed at an industrial scale [23], accompanied by an extensive encyclopaedia of relevant research data. The use of biomass and other bioenergy resources as a substitute for fossil fuels is expected to maintain a steady increase in the future [10, 18]. In Africa, few efforts have been made to study and promote the waste-to-energy concept. With regards to Cameroon in particular, only a few holistic and theoretical analyses have been carried out. Mboumboue and Njomo [1], evaluated the energy potential of wood-based residues amongst others, quantifying the calorific value of hog wood as 19.40 MJ/kg. Ackom et al. [4] reported the calorific value of wood thinning generated in Cameroon to be 18.30 MJ/kg. Despite these efforts, there are few practical and experimental data available for the physiochemical characterisation of this bioenergy resource in the local context.

The main objective of this paper is to illustrate the possibility of a profitable energy generation from wood-based waste generated in the metropolitan city of Yaounde while also investigating how this waste is managed. The ready availability and low cost associated with this waste stream compared to others are worth exploring, on the one hand as a waste management strategy encouraging the "close-the-loop" concept, on the other hand, as an energy alternative and solution to satisfy the energy demand in the country.

Materials and methods

This work was carried out in Yaounde, situated between latitudes 3°45′50″ and 3°59′55″ North and longitudes 11°22′40″ and 11°30′25″ East with an altitude of 760 m. Yaounde is the chief town of the Centre Region of Cameroon. The urban centre is composed of seven Subdivisions that all belong to the Mfoundi Division. The study was realised in five of these seven Subdivisions, namely: Yaounde II, III, IV, VI, and VII. Yaounde is the capital of the country and receives people from all walks of life. It offers many employment opportunities because of enhanced social and commercial activities compared to other parts of the country and therefore has a dense population and consequently higher demand for certain goods and services including wood products and energy. More so, most of the wood transformation units in Cameroon are located in this region hence, the production of huge amounts of waste [24]. Even though the area chosen is not a forest zone, its geographical location relative to source and export (or market routes) is strategic; the reason why more and more wood transformation units are based in this area. Figure 1 shows the map of our study area.

To attain the objectives of this work, both quantitative and qualitative research approaches were employed. Primary data was acquired through a questionnaire distributed to the wood industry operators, and a direct observation while on the field. Furthermore, sawdust samples were collected and taken to the laboratory for physiochemical characterisation. This sawdust was a mixture of different wood species processed in the study area. The test samples were collected from a sawmill selected as a representative case study, with the choice based solely on the criterion of wood processing capacity. This has allowed evaluating the feasibility of electricity auto-generation from wood waste



Source: CMR COD-AB

Fig. 1 Map of Cameroon showing the various regions (left) and partition of Subdivisions in Yaounde (right) of the Centre Region generated at the wood transformation unit (WTU). Laboratory results together with information from previous studies [22] provided input data for modelling of power generation by a gas turbine using Cycle-Tempo thermodynamic software [25].

Fieldwork

This phase of the work started on October 22nd and ended on December 12th of 2019. Inquiries were made through the administration of a semi-guided questionnaire to more than 100 sawmill and wood workshop owners and operators located in five of the seven subdivisions of Mfoundi Division, Yaounde. The questionnaire established was divided into five parts: (1) identification of the respondent; (2) their social aspect: the age and status of the individual amongst others; (3) the economic aspect: status of the enterprise, the quantity of sawdust produced and its handling, familiarity with biofuels and willingness to engage in transformation processes of wood waste into energy amongst others; (4) the health and environmental aspect: the consciousness of the individual concerning the sawdust dangers to their health and environment amongst others; and (5) miscellaneous: extra and useful information obtained from the field addressing preoccupations not initially envisaged in the above four parts. Besides, the GPS coordinates of every visited WTU were noted.

Determination of bulk density and particle size

The particle size of sawdust was determined through sieve analyses using a precision balance and a sieve set with mesh wire cloth ranging from 0.08 to 6.30 mm in size.

To determine the bulk density of the sample, a container of known volume and mass was filled with the sawdust sample with intermittent shaking to ensure the elimination of the air voids as much as possible. The bulk density was defined as the ratio of the sample mass to its volume (Eq. 1).

$$\text{Bulk density} = \frac{m - m_0}{V}, \tag{1}$$

where: m is the mass of the sample and container, m_0 the mass of the container and V is the volume of the container.

Proximate analysis

A series of tests, including moisture content, ash content, volatile matter, and fixed carbon contents, were aimed at characterising the fuel properties of the sawdust and to determine its suitability for biofuel production.

Moisture content (MC)

Petri dishes were cleaned and dried in an oven for 30 min. A sawdust sample was then placed in the petri dish and weighed. The weighed sample was dried in an oven at a temperature of 105 ± 3 °C for approximately 2 h. The oven-dried sample was cooled in a desiccator and then weighed to the nearest 0.001 g. This procedure was carried out in triplicates. Equation 2 was used to determine the moisture content (MC) as a percentage:

$$MC = \frac{m_1 - m_2}{m_1} \times 100\%, \tag{2}$$

where m_1 is the initial mass of the sample before drying, and m_2 the mass of the sample after drying at 105 ± 3 °C.

Ash content (AC)

The sawdust sample was placed in a crucible and dried at a temperature of 105 ± 3 °C for 2 h after which it was again weighed. The dried sample in the crucible was heated in a furnace at 500 ± 15 °C for 4 h. The burnt sample was withdrawn, cooled in a desiccator, and then weighed. This procedure was carried out in triplicates. The percentage of ash content was calculated using Eq. 3:

$$AC = \frac{m_3}{m_2} \times 100, \tag{3}$$

where m_3 is the mass of residue after incineration at 500 °C.

Volatile matter (VM)

With the ash content test which was carried out in triplicates, the volatile matter was calculated as the mass loss between the incinerated sample and the dried sample. Equation 4 was used to determine the volatile matter content as a percentage on a dry and ash-free basis:

$$VM = \frac{m_2 - m_3}{m_2} \times 100. \tag{4}$$

Fixed carbon (FC)

Fixed carbon was determined by subtracting the mass of the volatile matter, moisture content, and ash content from the initial mass of a sample of fuel, a method commonly known as by difference i.e.

$$\mathrm{FC} \ = 100\% \ (\mathrm{AC}\ \mathrm{VM}\ \mathrm{MC}). \tag{5}$$

Energy content

To estimate the amount of energy that can be obtained from wood waste, it was assumed that the sawdust will be pyrolyzed for energy production. So, the calculations were based on the amount of syngas that can be obtained from sawdust.

The energy content of biomass is the amount of energy stored in a given unit of a biomass sample and is usually measured as the heat of combustion. Usually, heating value (HV) (or calorific value, CV) is used as a measurement for the energy content. There are two heating value types frequently used, i.e., higher heating value (HHV) and lower heating value (LHV).

The HHV (in MJ/kg) of biomass on a dry basis was estimated from the results of the ultimate analysis [22] and ash content from proximate analysis according to Eq. 6 [22, 26]:

$$\begin{aligned} HHV_{DB} = 0.3491EC_{C,DB} + 1.1783EC_{H,DB} + 0.1005EC_{S,DB} \\ - 0.0151EC_{N,DB} - 0.1034EC_{O,DB} - 0.0211A_{DB,} \end{aligned} \tag{6}$$

where EC means elemental composition, C, H, S, N, and O stand for carbon, hydrogen, sulphur, nitrogen, and oxygen respectively, A_{DB} represents the ash content on a dry basis.

The combustible gas components of syngas are H_2, CO, and CH_4 whose standard HHVs are 12.76 MJ/m^3, 12.63 MJ/m^3, and 39.76 MJ/m^3 respectively [27]. With these values, the energy content of wood gas was estimated according to Eq. 7:

$$LHV_{\text{syngas}}(MJ/m^3) = 12.76 \times \%H + 12.63 \times \%CO + 39.76 \times \%CH_{4,} \tag{7}$$

where %H, %CO, and %CH_4 represent the percentage compositions of hydrogen, carbon monoxide, and methane respectively in the syngas.

The average thermal conversion efficiency of wood gasifiers or the gasification process was computed using Eq. 8 [28]:

$$\eta_{\text{gas}} = \frac{\Delta H_{\text{gas}}(MJ/m^3) \times V_{\text{gas}}(m^3)}{\Delta H_{\text{wood}}(MJ/kg) \times 1(kg)} \times 100\%, \tag{8}$$

where ΔH_{gas} is the calorific value of the syngas produced from one kilogram of wood, ΔH_{wood} is the net calorific value per kilogram of wood and V_{gas} is the volume of gas obtained from one kilogram of wood.

Knowing η_{gas}, the amount of syngas obtainable from wood waste generated per day at our case study site was estimated using Eq. 9:

$$V(m^3/\text{day}) = \eta_{\text{gas}} \times m \times V_{\text{gas,}} \tag{9}$$

where m represents the mass of sawdust produced per day, V the volume of gas in m^3/day and η_{gas} the syngas to biomass ratio.

The volume calculated from Eq. 9 alongside the calorific value of the syngas were used to compute the energy potential of the wood gas through Eq. 10:

$$EP(MJ/\text{day}) = V \times LHV_{\text{syngas,}} \tag{10}$$

where EP represents the energy potential.

The daily electric power conversion potential P_{ep} of the obtainable syngas was estimated using Eq. 11:

$$P_{\text{ep}} = \text{LHV}_{\text{gas}}\left(\frac{MJ}{m^3}\right) \times V(m^3) \times \eta_{\text{gas}} \times \frac{1\text{kWh}}{3.6(\text{MJ})} \tag{11}$$

Assuming a value for the electric efficiency of a gas engine as provided in [29], the achievable power output was obtained following Eq. 12:

$$P_{\text{el}}(\text{kWh}) = \eta_{\text{electric}} \times P_{ep} \times (1 - \%\text{loss}) \tag{12}$$

where P_{el} represents the daily electric power, η_{electric} is the electric efficiency of the system.

The energy potential for the various subdivisions in Yaounde per week was finally estimated using the estimates of the wood waste quantities generated in each of the five subdivisions along with the estimated HHV of the sawdust. This was done using Eq. 13:

$$EP_x = M \times HHV_{DB} \tag{13}$$

where EP_x represents the energy potential per Subdivision x and M (tons/week) is the amount of sawdust produced per Subdivision.

Modelling and simulation

The model used was adapted from ASIMPTOTE [25]. The objective of the model was to thermodynamically analyse the energy requirements of “La Forèstiere de Moloundou” (LFM) sawmill concerning the energy potential of the waste generated at their site. For this purpose, the trial version of the software Cycle Tempo, release version 5.1 was employed. It is a robust software for thermodynamic analysis and simulation of energy systems. The model inputs include fuel type and composition, energy value, pressure, oxidiser, temperature, conversion and electric efficiencies while the output includes mass and volume flows, pressure, temperature, enthalpy, and electric power. Table 1 gives the operating conditions for the model developed using the software.

Table 1 Model operating conditions

Model data and operating conditions		
Component	Parameter	Value
Air source (oxidiser)	Mass flow	Calculated by software
	Outlet pressure	1.013
	Outlet temperature	15 °C
Fuel source (syngas)	Outlet temperature	15 °C
	Mass flow	Calculated by software
	Out pressure	15 bar
	LHV	5600 nm^3/s
Air compressor	Outlet pressure	12 bar
	Isentropic efficiency	85%
	Mechanical efficiency	95%
Combustor	Energy equation code	1 (defines mass flow)
	Estimate of the oxidant-fuel ratio	2%
	Pressure at which equilibrium is calculated	12 bar
	Temperature at which chemical equilibrium is calculated	1000 oC
	Pressure loss in the apparatus	0.25 bar
Cooling step	Pressure loss in the apparatus	0 bar
	Energy flow to the environment	2000 kW
	Estimate for the mass flow	600 kg/s
Turbine	Turbine code	0 (general type)
	Isentropic efficiency	85%
	Mechanical efficiency	95%
	Inlet temperature	100
	Inlet pressure	Calculated using Traupel's formula
Generator	Generator efficiency	35%

The following assumptions were made in the simulations:

- Syngas used in the model is produced through a gasification process, has the following composition: CH_4 (2%), CO_2 (12%), N_2 (48%), CO (20%) and H_2 (18%).
- Power output specified is supplied by turbine (to the generator) and corresponds to the monthly energy consumptions at LFM sawmill (that is 13 MW).
- The environment definition of the model simulation used in exergy calculations; pressure (1.01325 bar), temperature (15 °C)
- Air composition (mole %): Ar(0.91), CO_2(0.03), H_2O(1.68), N_2(76.78), and O_2(20.60).

Results

Location of wood transformation units

A total number of 136 WTUs were visited in five of the seven Subdivisions of Mfoundi Division, Yaounde, and 100 (73.53%) of them responded to the questionnaire. The GPS coordinates of all the WTUs visited were documented and used to produce the map of the location of the WTUs (Fig. 2).

These WTUs were distributed within the study area as shown in Fig. 3.

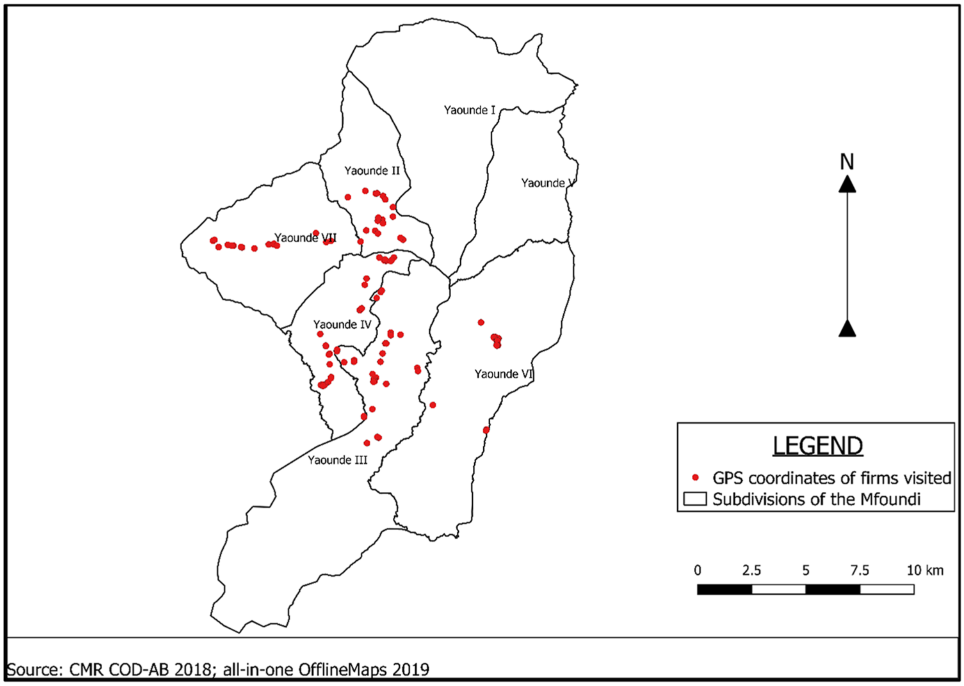
Wood species and quantity of wood waste generated

The wood types censored in the local markets are shown in Fig. 4.

The two main types of wood wastes encountered in the field surveys were wood shavings (curly) and wood sawdust (smaller and dust-like) with the former being dominant in terms of quantity produced. The estimates were made in the field in units of bags (Fig. 5) and then converted to mass quantities using the volume of the bags (assumed to equal the volume of the sawdust) and the bulk density of the sawdust.

The estimate of the quantity of sawdust produced by WTUs in each Subdivision is presented in Table 2.

Fig. 2 Map of Yaounde with the localisation of visited WTUs



Source: CMR COD-AB 2018; all-in-one OfflineMaps 2019

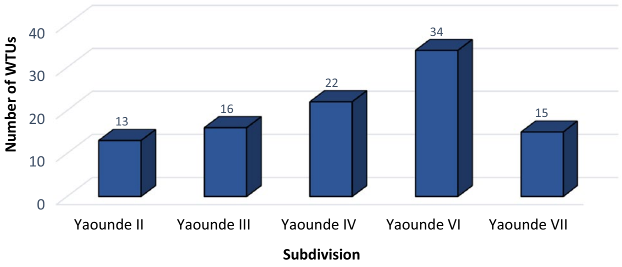


Fig. 3 Distribution of WTUs in Yaounde

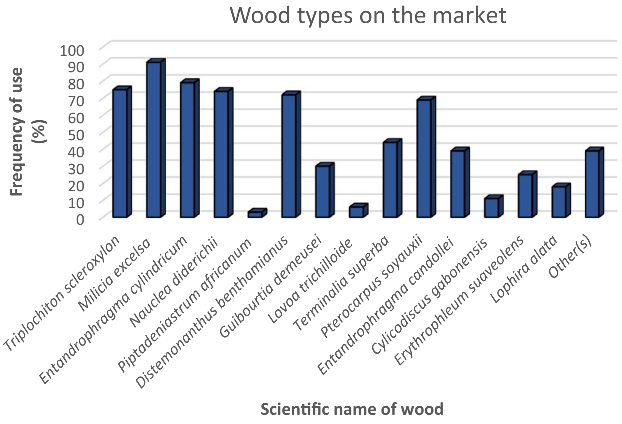


Fig. 4 Most common types of wood used in WTUs in Yaounde

Fig. 5 100 kg bags with sawdust

Table 2 Energy potential produced per subdivision of Yaounde

Name of subdivision	Number of WTUs	Amount of sawdust generated (tons/week)	Primary energy potential (GJ/week)
Yaounde II	13	30.25	607.41
Yaounde III	16	38.25	768.05
Yaounde IV	22	77.75	1521.04
Yaounde VI	34	105.5	2118.42
Yaounde VII	15	35.5	712.83
Total	100	287.25	5727.75

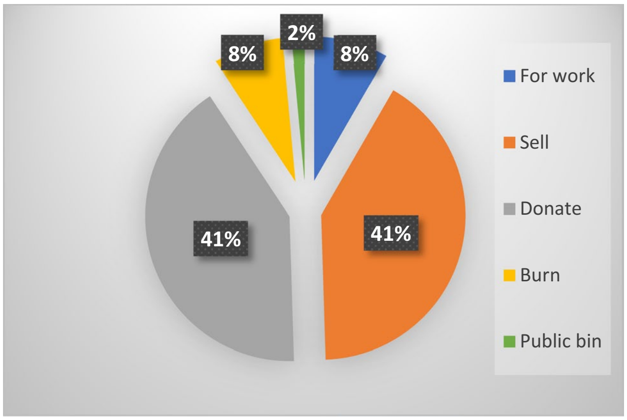


Fig. 6 Statistics of wood waste handling

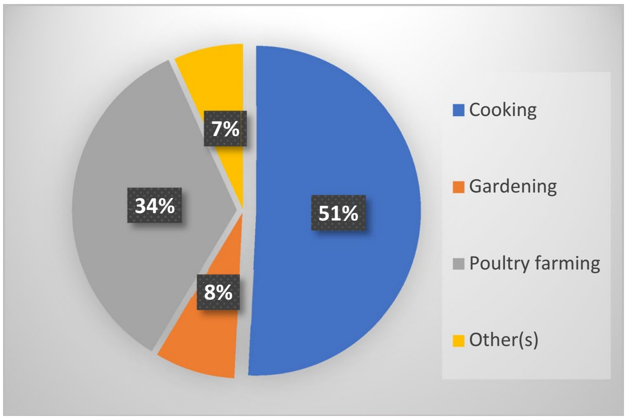


Fig. 7 Uses of sawdust

Wood waste handling

With respect to the handling of the wood waste, it resulted that about 41% is sold but considerable quantities are also given out free of charge to interested parties. The sawdust is generally sold at higher prices (ten times more) compared to shavings; on average, a bag (Fig. 5) of sawdust costs about 2.5 dollars and the same bag of shavings, about 0.8 dollars. For WTUs located in residential areas, 41% of operators often compensate for the nuisance and pollution by providing wood waste to neighbouring inhabitants free of charge (Fig. 6). Furthermore, it was found that the finest category of sawdust is used by carpenters for filling up cracks in furniture. It was also observed that some firms disposed of their waste through open burning (8%) and others preferred throwing in nearby bushes, swamps, and water channels. Besides, nearly all WTUs had huge heaps of sawdust within their workspace. The statistics for wood waste handling resulting from our findings are presented in Fig. 6.

None of the WTUs was found to use its waste for bioenergy production. Rather, the waste was collected and used mainly as wood (51%), for poultry farming (34%) and lesser proportions for market gardening and other activities as indicated in Fig. 7. Furthermore, it was uncovered that the fine proportion of the sawdust is used in the cleaning of ceramic tiles during their placement.

In most of the visited WTUs, heaps of wood waste were mounted in and around the worksite. Some of the heaps were seen to block runoff during the rainy season and eventually served as a dumpsite for other waste types (Fig. 8a). One other method for handling wood waste was through open burning, a practice that was observed in about 5% of the study sites (Fig. 8b). Moreover, it was observed that sawdust in most WTUs usually occupied much-needed space and would impede movements, slowing down work. To manage this, some human labour would sometimes be dedicated to digging out machines buried in the heaps of wood waste (Fig. 8c). In other WTUs, wood waste was disposed of by throwing in the bushes and swamps surrounding the area (Fig. 8d). Furthermore, in some establishments, it was observed that uncollected sawdust was often pushed and dumped outside in the open space where it formed heaps that would eventually be transported and disposed of in a prepaid zone far away from any residential area; the location of the disposal site was not disclosed. During the rainy season, this waste mixes up with mud and traps rainwater thereby forming fertile mosquito breeding grounds, putting workers in danger of contracting malaria. Meanwhile, in the dry season, the dust is dried up by the sun and due to their fine nature are easily transported in the atmosphere and dispersed by wind. Figure 9 depicts this situation in one of the sawmills.

Case study

The case study was carried out to evaluate the potential of autonomous electricity generation from wood waste by wood processing units. “La Forèstiere de Moloundou_Sciérie” (LFM) sawmill was selected for this purpose because of the relatively high volumes of wood (40–50 m^3) it transforms per day. The sawmill operates six days a week implying a processing capacity of about 240–300 m^3 of timber per week. LFM transforms the following type of wood species; Tali, Okan, Padouk, Kotali, Bilinga, Iroko, Sapelli, Pachyloba, Movingui, Doussie, and Moabi into lugs of various dimensions intended solely for the foreign market.

There are three main types of wood waste detected at the LFM sawmill; sawdust, offcuts, and bark. The sawdust produced at LFM is collected and sold by the local employees to augment their private incomes. These employees collect sawdust in the range of 40–50 bags a day which is equivalent to about 1 ton of sawdust per day.

The corresponding quantities of waste generated in terms of volume (V) and mass (m) were then estimated at 36.82 m^3/week and 6.76 tons/week respectively.

Fig. 8 Popular methods of sawdust disposal (**a**) Heaps blocking runoff (**b**) Burning (**c**) Digging out machine overwhelmed by sawdust (**d**) In bushes

Fig. 9 Heap of wood waste at LFM sawmill site

Physiochemical characterisation

Particle size determination and bulk density

Results from the particle size determination showed that the largest composition is within the range 0.3–1.00 mm. Figure 10 illustrates the sawdust particle size distribution of the sampled sawdust.

The bulk density of the wood waste sampled equals 184.64 kg/m^3.

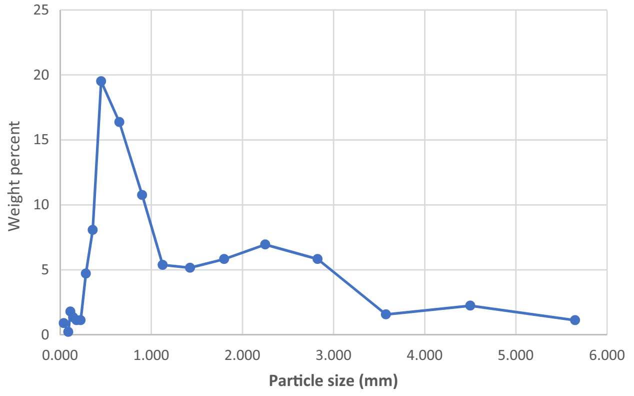


Fig. 10 Sawdust particle size distribution

Proximate analysis

The results of the proximate analysis gave 17.74 ± 0.27%, 3.91 ± 1.54%, 74.62 ± 1.47%, and 3.73% for moisture content, ash content on a dry basis, volatile matter on dry ash basis and fixed carbon respectively.

Energy content

According to the equations provided in Sect. 2.4, the heating value of the sawdust is quantified as:

$$\mathrm{HHV}_{DB} = 20.08\ \mathrm{MJ/kg}.$$

Assuming the compositions of the combustible gas fractions of the syngas [22] to be $H = 18\%$, $\mathrm{CO} = 20\%$, and $\mathrm{CH_4} = 2\%$, as elaborated in Eq. 7, the heating value of the obtainable syngas is:

$$LHV_{\mathrm{syngas}} = 5.62\ \mathrm{MJ/m^3}.$$

On average, a kilogram of dry biomass produces about 2–3 $\mathrm{m^3}$ of syngas under standard conditions [28], hence, knowing $\mathrm{LHV_{syngas}}$ and $\mathrm{HHV_{DB}}$, the biomass conversion efficiency is:

$$\eta_{\mathrm{gas}} = 69.95\%.$$

For LFM sawmill, using the adopted methodology and Eqs. 9, 10, 11, 12, the following parameters were estimated:

- Amount of waste produced at LFM per day, $m = 1127$ kg/day
- The average volume of gas per day = 1971 $\mathrm{m^3}$/day
- The energy content of this gas = 10,082 MJ
- Daily production of primary energy, $P_{\mathrm{ep}} = 3075$ kWh/day
- Taking the electric efficiency of the system equal to 35% and energy loss 40%, the obtained electric power is $P_{\mathrm{el}} = 645.78$ kWh/day

Using a similar procedure, it was possible to estimate the energy potential produced per municipality (Table 2).

Modelling and simulation with cycle tempo

In the adopted model, the power output value was motivated by the estimated average monthly energy consumption for the LFM sawmill. The model was developed using gasification syngas as fuel, with a characteristic calorific value of 5.6 $\mathrm{MJ/m^3}$ as obtained from the energy content calculations.

It resulted from the simulation that 13 MWh of energy would require 27.955 kg/s of syngas which translates to a volume flow of 1.7850 $\mathrm{m^3/s}$ at a pressure of 15 bars. Furthermore, the power output of 13 MW was averaged over 1 month (30 days) to give 433.33 kW/day which was approximated to 450 kW/day and was fixed as output power in the model. The simulation provides the results displayed in Fig. 11, which suggest a mass flowrate of syngas equal to 1.31 kg/s and a volume flow rate of 0.08 $\mathrm{m^3/s}$ at a pressure of 15 bars. Figure 11 also shows the airflow and flue gas flowrates.

The simulation was further tested under a different set of conditions. For example, a decrease in the isentropic efficiency (used to measure the degree of degradation of energy in a steady flow process) of the turbine component, below 50% produces a negative mass flow and increases the mechanical power of the turbine. At an inlet temperature of 15 °C and pressure of 15 bar, for a pre-set power output of 13 MW, the net energy and exergy efficiencies were 8.304% and 9.655% respectively. An increase in the outlet pressure of the air source considerably reduces the mass flow of both air and the fuel, while increasing the amount of energy supplied to the environment (enthalpy); this however leads to an increase in the energy and exergy efficiencies. Meanwhile, an increase in the outlet temperatures of the air source leads to an increase in the mass flow of the two streams, while leading to a decrease in the enthalpy and consequently, a decrease in both the energy and exergy efficiencies.

Note that the pressure and temperature at which equilibrium is calculated are both functions of the inlet pressure and temperature of the air and fuel sources, hence, evaluated automatically by the software.

The composition of the different fluids was categorised by the software using streams 1, 2, and 3 corresponding to air, flue gases, and syngas, respectively. Figure 12 shows the percentage compositions of the individual gases.

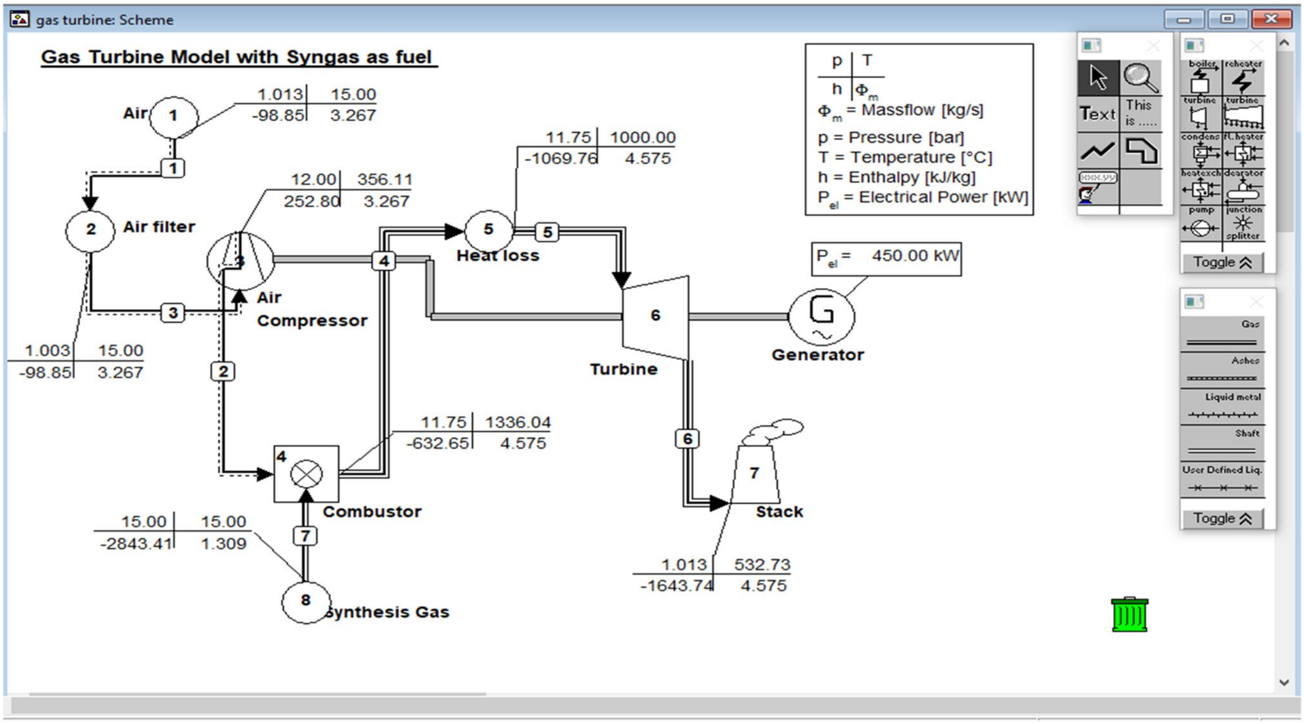
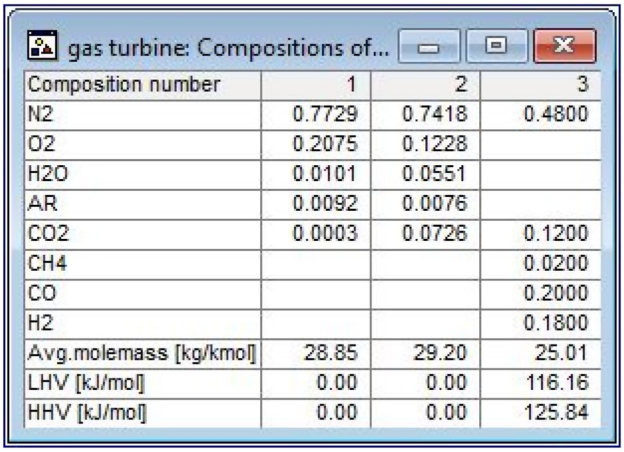


Fig. 11 Gas turbine model with simulation results of average daily energy consumption



Composition number	1	2	3
N2	0.7729	0.7418	0.4800
O2	0.2075	0.1228	
H2O	0.0101	0.0551	
AR	0.0092	0.0076	
CO2	0.0003	0.0726	0.1200
CH4			0.0200
CO			0.2000
H2			0.1800
Avg.molemass [kg/kmol]	28.85	29.20	25.01
LHV [kJ/mol]	0.00	0.00	116.16
HHV [kJ/mol]	0.00	0.00	125.84

Fig. 12 Gas compositions along various streams

Discussion

Wood industry operators, wood waste production and management

A total of 136 WTUs were visited and 100 regularly filled questionnaires were returned in the study area. Results indicate that Yaounde VI had the highest number of WTUs (33); this was attributed to the numerous wood markets that sell sawn wood in this municipality.

As observed in the field and confirmed by woodworkers, the amount of produced wood waste depends on the type of equipment used and on the wood species being transformed. Hardwood species, such as “Okan” and “Tali”, produce lesser quantities of waste than softwood species such as “Ayous”. This property is associated with the different wood densities. In the Yaounde VI subdivision, the 33 WTUs that took part in the study represent only about half of the actual number of WTUs present in that area and collectively, they produce about 106 tons of wood waste per week on the average. As observed in the field, less than half of this waste is collected for ultimate exploitation hence, the need to harness this potential is wasting away and is rather polluting the environment.

Since shavings are more voluminous, they are generated in lesser time compared to sawdust and this is the main aspect governing the prices at which the wood waste is sold to women for cooking purposes and poultry farmers. Generally, women who buy wood waste for cooking purposes prefer sawdust to shavings because of its thermal efficiency and its ability to last longer (this property can be attributed to particle size) but tend to acquire more often shavings because it is cheaper. Conversely, poultry farmers prefer wood shavings especially of softwood species which is used to generate and conserve heat for table birds thereby reducing expenditure on artificial heat sources. It is worth noting that some wood sector operators indicated that they prefer revenue returns from marketing wood wastes to thermochemical conversion and energy valorisation of the waste, due to fear of high investment costs.

Even though some respondents attested to deliver wood waste free of charge as a way of managing the waste, heaps of wood waste could still be sighted in and around the workspace. This often forces them to deal with the waste through unsustainable approaches in concordance with findings by Owoyemi et al. [20]. It should be said that open-air disposal and burning of wood waste cause air pollution with consequences such as respiratory illnesses (particulate matter inhalation) and climate change. The reasons put forward by the operators for such poor management of sawdust could be attributed to: (1) the perception a useless waste; (2) the inconvenience created by large heaps of sawdust, and (3) the absence of active local and national policies regarding the management of such waste types in line with [14]. Nevertheless, 84% of people were willing to valorise their lignocellulosic waste but were limited by financial constraints.

Energy potential of sawdust

Small biomass particle sizes increase surface area for reactions during an energy conversion process, leading to higher heating rates as well as higher energy efficiencies with increased processing rate. Due to this property, less char and condensates are produced during incineration while the production of lighter gases is favoured. Therefore, it is well known that the process flowrate and the produced volume of syngas increase with small particle biomass size. According to [30], it can be affirmed that the dominant proportion of the sampled sawdust (0.4 to 1 mm) obtained in this study would be of ideal particle size for optimum thermochemical conversion and does not require any further shredding or particle size reduction. This will save energy and time that would have been employed in the shredding process thereby reducing overall processing cost.

The heating value of the produced gas greatly depends on the moisture content of the feedstock because additional heat is required to dry high moisture content feedstock thereby increasing the energy consumption which otherwise would have been used for subsequent processes. Compared to data from the literature, the sawdust sample collected in Yaounde is characterised by a relatively high moisture content (17.74%) and so would require pre-treatment such as sun drying or any artificial drying methods before gasification or pyrolysis. Ideally, the moisture content should be below 10% for pyrolysis according to [31]. However, in the case of gasification, the higher temperatures can promote the production of H_2 and higher calorific value for the gas.

The ash content which is the fraction in biomass that is composed of incombustible mineral material is present in the form of inorganic compounds like sodium, potassium, calcium, silicon, phosphorus, and chlorine. High ash contents make combustion challenging due to the potential release of the ash. The presence of ash in syngas may cause problems of deposition and corrosion of equipment that utilizes syngas such as a gas turbine [32]. Besides, the melting of ash during combustion causes fouling (forming deposits on combustor surfaces), sintering, and slagging (hard chunks of material left at the bottom of the combustor chamber) [33] that would require a regular cleaning and high maintenance of the gasifier. The sample collected at LFM is characterised by a relatively low ash content (3.91%) compared to 6.5% obtained by Hameed et al. [33], thus suggesting that the sawdust would have a low level of negative influence on the gasification efficiency as a result of ash content.

Moreover, the volatile matter content, which gives an idea of the reactive nature of the biofuel from biomass, was approximately 75% indicating that the biomass has a high organic content. This implies that most of the calorific value would be given off as combustion vapour upon carbonisation. This volatile portion of combusted biomass would be composed of gases such as methane, hydrocarbons, hydrogen, carbon monoxide, nitrogen, and some unburned gases.

The fixed carbon on its part refers to the carbon that remains when the volatile matter has been given off. It is, therefore, an indication of the uncharred carbon; the lower the fixed carbon the higher the fuel convertibility. The calculated fixed carbon amounts to about 3.73% which is quite low, suggesting that the LFM wood waste is of the high convertibility.

By the way, the choice of the study [22] from which ultimate analysis results were adopted for use in the calculations was driven by the fact that Cameroon and Nigeria, which are neighbouring countries, both belong to the same tropical rainforest zone hence, similar wood species. Moreover, the analyses reported in [22] are fairly recent (2019). The high hydrogen and oxygen contents resulting from the ultimate analysis suggest a high energy potential of the fuel, meanwhile, the low Nitrogen and Sulphur content (which are solicited) suggest that a small amount of their oxides will be produced during combustion, hence the low impact on the environment in line with [34]. These results attest the suitability of the wood waste characterised in this work, for energy conversion through a gasification process.

The estimated gross calorific value shows that the sampled sawdust possesses a high energy potential and this was in agreement with results from [1, 4, 35], and typical of lignocellulosic biomass. The heating value of the obtainable syngas, together with the HHV of the sawdust give a conversion efficiency of approximately 70%. This high conversion efficiency shows that the energy-rich sawdust produced in

Yaounde could be harnessed positively for syngas production as an economical solution to remove this waste from the wood industry through an environmentally-friendly and energy-efficient process [34].

Electric power generation using syngas

The daily energy consumption is quantified by averaging the energy value of 13 MW required over one month (30 days). The Cycle-Tempo simulation with this output power suggests that about 302.40 m^3 or 4712.40 kg of gas, at 15 bars are required to produce 450 kWh of electricity, which entails that 1.49 kWh primary energy would be produced for every cubic metre of gas. Furthermore, the primary electric power potential per day obtained by calculations from the characterisation of the sawdust is 3075.16 kWh/day; considering 35% electric efficiency and 40% losses due to conversion and gas cleaning [29] before utilisation, the energy delivery amounts to about 645.7830 kWh/day. This means that 0.38 kWh of energy can be produced per cubic metre of gas achievable from the wood sawdust produced at the LFM sawmill.

Based on these results, it can be stated that the energy demands of LFM sawmill could be largely satisfied with the energy valorisation of their by-products. This points to the fact that wood processing mills can be self-sufficient in the generation of electricity and use from its waste. However, because these results have been obtained partly based on some assumptions, more experimentation, in particular, the specific quantification of the syngas to biomass ratio and gas compositions of the biomass sample, would be required in the future to confirm the outcomes here presented.

Conclusion

The major objective of this work was to evaluate the potentials of generating electricity from wood workshops and timber mills in Yaounde, Cameroon via a biofuel production process. The total quantity of wood waste produced in Yaounde represents a total energy production potential of 5727.25 GJ/week. The calorific value of the sawdust sample was quantified as 20.08 MJ/kg and that of the obtainable syngas was estimated as 5.62 MJ/m^3. From thermodynamic modelling, it resulted that a daily energy production of 450 kWh, which corresponds to the energy required at LFM sawmill per day, would require 302.40 m^3 of syngas at a pressure of 15 bars. LFM sawmill was estimated to produce about 1.13 tons of sawdust per day from which about 1970.55 m^3 of syngas could be obtained, and consequently about 745.78 kWh of electricity per day. Therefore, sawdust generated at LFM could satisfy the energy demand of the sawmill. In conclusion, based on the evidence by this study, it can be affirmed that WTUs in Yaounde generate enough wood waste that can be harnessed energy-wise either individually by the firms producing it or, collectively, by the local governments to supplement electricity to local inhabitants. This work lays down a framework contributing to policy development in the sustainable management of wood waste.

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