Life Cycle Assessment Model for Biomass Fuel Briquetting

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ABSTRACT

Purpose

Previous Life Cycle Assessment (LCA) studies of biomass briquetting have shown wide variations in the LCA outcomes as a result of variations in LCA methodological parameters and briquetting technological parameters. An LCA model of biomass briquetting was therefore developed to enable transparent comparison of life cycle environmental impacts of briquetting with individual or blends of biomass feeds with a variety of technological options.

Methods

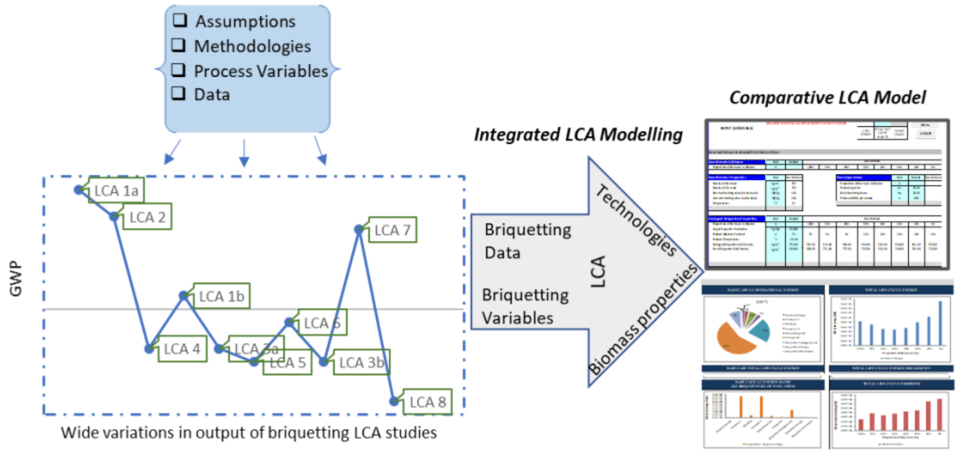
The model was developed according to the standard LCA procedure of ISO14044. A comparative approach was utilised, and a set of integrated excel worksheets that describe process flows of material, energy and emissions across different units of the briquetting process was used in developing the model components.

Results

The main model components include materials and process inventory databases derived from standard sources, main process calculations, user inputs and results sections. The model is open-access in a user accessible format (Microsoft Excel). A representative case study with mixed rice husks and corn cobs was used in validating the model. Results showed that the briquetting unit made the largest contribution, 42%, to the total life cycle operational energy of the briquetting system. For all the blends of rice husks and corn cobs explored in this study, the total life cycle energy of briquetting was in the range 0.2 to 0.3 MJ MJ^{-1}. For the same blend ratios, a total life cycle energy of briquetting in the range 0.2 to 1.7 MJ MJ^{-1} was also obtained with change in other LCA input parameters, in a sensitivity test. An increase in rice husk content of the blend increased the environmental impact of briquetting in terms of global warming potential (kg CO_2-eq), acidification potential (kg SO_2-eq), human toxicity (kg 1,4-DB-eq), ozone layer depletion (kg CFC-11-eq), and terrestrial ecotoxicity (kg 1,4-DB-eq) per MJ briquette energy content, as it was associated with a lower briquette density, which increased the energy required for handling.

Keywords: LCA; densification; modelling; energy; GWP

Graphic Abstract



Statement of Novelty

Life cycle assessment models of bioenergy sources have been focused on specific processes such as biomass cultivation stage and transportation fuels. Existing models such as Agrifood LCA model and more general LCA software (e.g., Simapro and GaBi) have limited process variables and data for briquetting processes resulting in increased time for data gathering, slower assessment, and limited flexibility to model and optimise specific briquetting process features. While some also attract high financial costs. The LCA model presented here utilises data specific to the context of briquetting to develop a life cycle inventory (LCI), and enable quicker assessment and greater flexibility to change, modify and optimise specific briquetting process features (depth and breadth of assessment), as well as reduce reliance on high cost software.

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1 Introduction

The densification of loose biomass materials into briquettes increases biomass bulk and energy density per unit volume, resulting in reduced transportation costs and storage space, as well as more uniform feeding into thermal conversion equipment [1,2,3]. The additional energy and cost have raised concerns over the sustainability and importance of biomass briquetting. Previous literature review of assessments of the life cycle environmental impacts of biomass briquetting [4] found significant variations in the outcomes. More recent studies also showed similar variations in the LCA outcomes of biomass briquetting [5,6,7]. The variations can be attributed to methodological choices in the life cycle assessment (LCA), as well as the technical process.

There is a need to understand the relationship between briquetting process variables and the life cycle environmental impacts. For example, biomass properties, such as density and moisture content, can affect the energy requirement needed for its densification. Likewise, differences in briquetting technology, such as equipment design capacity, energy consumption and material of construction, can affect its environmental impact. It is also important to understand how interaction between these variables affects the LCA outcome. One way of addressing these issues is the development of a comparative LCA model that integrates key briquetting process variables, to allow practitioners the flexibility to change specific features of the system and gain an understanding of the effect of these changes on the LCA outcome.

In recent years, LCA models have been developed for various systems [e.g., construction: [8], waste management: [9], to address LCA methodological issues and improve speed and flexibility of assessment, as well as understanding of the outcome. However, in the bioenergy sector, these models have been focused on other processes such as: 1) the Agrifood LCA model [10], which focuses on the biomass cultivation stage, 2) the Greenhouse gases Regulated Emissions and Energy use in Transportation (GREET) software [11], which focuses on transportation fuels, 3) the CAMPUBIO [12], which focuses on LCA of various types of algal biomass and technologies, and 4) the Biofuel Energy Systems Simulator (BESS), which focuses on assessing the life cycle energy and greenhouse gases (GHG) emissions of corn to bioethanol system [13].

These models and more general LCA software such as Simapro [14], GaBi [15] and openLCA [16] have limited process variables and data for briquetting processes, resulting in increased time for data gathering, slower assessment, and limited flexibility to model specific briquetting process features. Some also attract high financial costs. The LCA model presented here utilises data specific to the context of briquetting to develop a life cycle inventory (LCI), and enable quicker assessment and greater flexibility to change, modify and optimise specific briquetting process features (depth and breadth of assessment), as well as reduce reliance on high cost software.

The specific objectives of this study were;

1. To develop key mathematical equations for calculating life cycle energy for different units and technological options of the briquetting system, using basic engineering principles.
2. To use the developed equations and impact assessment methods to create an open-access user accessible format (Microsoft Excel) of the model.
3. To generate inventory specific to the briquetting process and integrate into the user model for further use.
4. To carry out a representative LCA case study with mixed rice husks and corn cob biomass.

2 Methodology

2.1 Model development

The LCA model was developed in accordance with the basic principles described by ISO 14044 [17]. A gate-to-gate system boundary was considered, and key units include loose biomass storage onsite, drying, crushing, conveying, blending/mixing, briquetting (densification), curing/cooling, packaging and briquette storage. A functional unit of 1MJ briquette energy was used in this study.

Figure 1 illustrates the overall approach used in developing the LCA model; it shows a set of integrated excel worksheets that describe process flows of material, energy and emissions across the different units of the briquetting process, and other components of the model. For each briquetting unit, mass and energy balance equations were developed using engineering principles and by applying the law of conservation of mass [18] to account for all materials within the system boundary (including losses).

Figure 2 shows the approach used in modelling the life cycle operational and embodied energies of the system, including primary production of machinery and building components, their transportation, fuel production, and fuel use in the briquetting plant (Figure 2).

Both operational and embodied energies are dependent on selected equipment duty (e.g., capacity, volume and mass restrictions), number of equipment units required and energy rating. The expected variations in feed biomass properties and briquette characteristics on equipment duty [2; 15] were accounted for by developing mathematical relationships that incorporate density, mass and volume.

The model adopts a comparative approach and allows assessment of up to ten cases of biomass blends with different technological options. It consists of four main sections including inventory, main calculations, user input and results (Figure 1). The main calculation section of the model uses the programmed mathematical equations in combination with user input and information collected from the inventory to estimate the number of equipment units required, the life cycle operational and embodied energies, and carbon emissions. The model calculates the environmental impacts and display the results by impact categories.

2.2 Allocation of burdens

Allocation in LCA deals with the attribution of an appropriate share of the environmental burden to different co-products in a system. A functional approach (the use of specific allocation factor such as mass, volume, energy content and energy input associated with various co-products in a multifunctional system), was used in the burden allocation to the biomass briquette as well as wastes (loose biomass and shattered briquette), and this was based on specific energy density of material. There is possibility of recycling the waste loose biomass and shattered briquettes but this depends on the briquetting process and properties of the wastes, as some of the waste materials may lose the original biomass properties and become less densifiable (e.g., in high temperature densification or addition of chemical binders).

The environmental burdens of various briquetting equipment components were calculated over the lifetime of the briquetting plant. In terms of the burden allocation, the energy used in equipment manufacture and maintenance (embodied impact) was separated from energy required to operate the equipment (operational impact).

The burdens of the briquetting plant building structure were based on the masses of the steel and concrete [16,17] components.

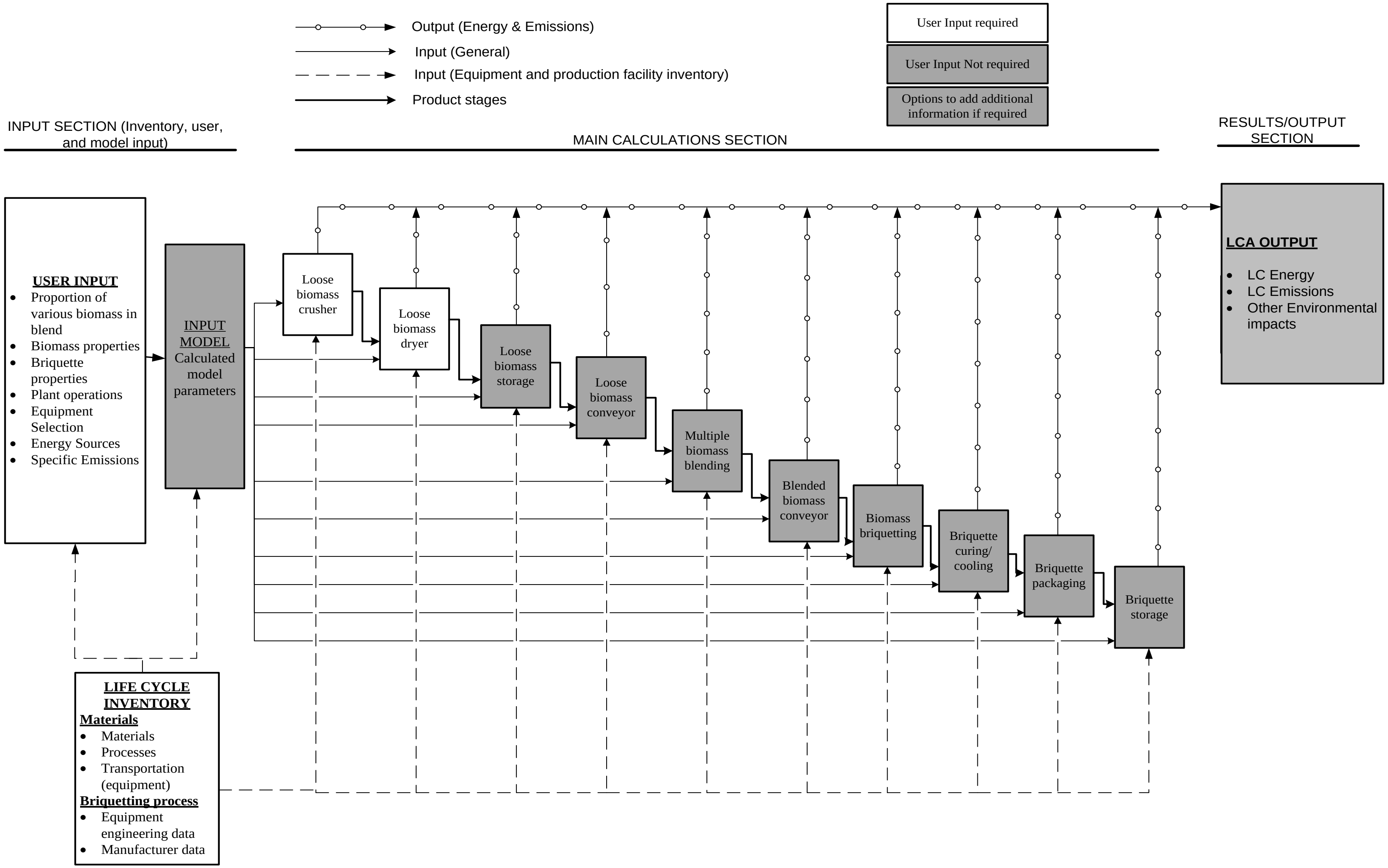

Figure 1: The LCA model framework for mixed biomass briquetting

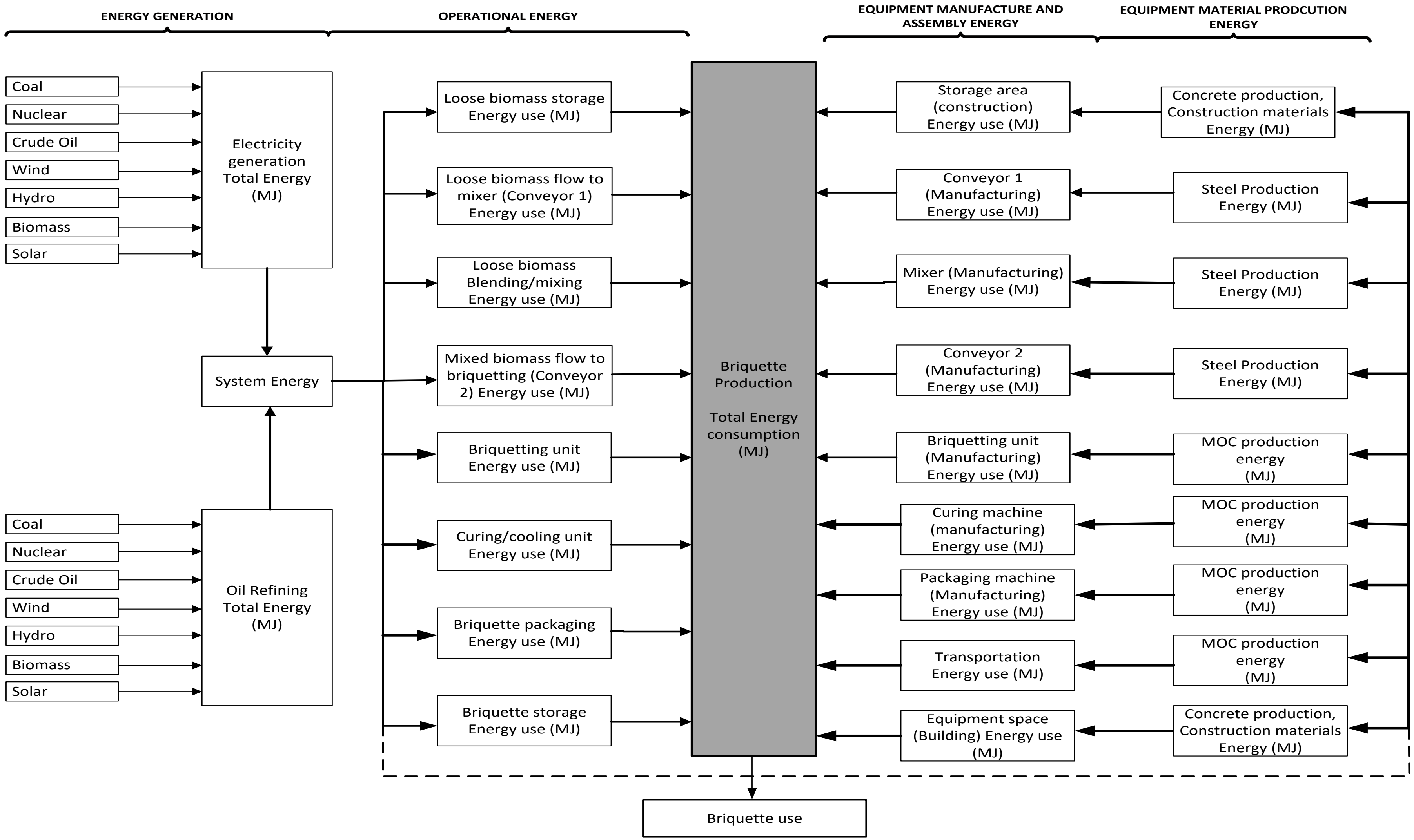

Figure 2: Energy analysis framework for biomass briquetting (MOC = materials of construction)

2.3 Life cycle inventory (database)

The life cycle inventory was built in the form of a database within the integrated worksheets Figure 1 to allow the user to select from a range of equipment (up to 30 options), materials and associated energy and emissions of processes related to the briquetting system. Two main data tabs describe: 1) the briquetting machinery database (engineering data), and 2) materials for this machinery, buildings, fuels and transport systems.

Foreground data on the briquetting process, such as equipment design and operational data, and their materials of construction (database 1), were collected from equipment manufacturers such as AGICO group [21] and Gongyi Lantian [22], and published process equipment compendia [23]. These sources were among the few established manufacturers of the briquetting process equipment.

Background data on materials, fuels and transport processes were collected from Ecoinvent v3 [21, via the Simapro platform], which is one of the most recognised standard LCI databases, with general process data and emission factors that are applicable for different geographical regions. In addition to the Ecoinvent data, construction materials inventory data were also collected from ICE [25] and the literature [17; 16].

2.4 Briquetting system mass balance equations

2.4.1 General approach

A simple mass balance across each unit of the briquetting process (Figure 3) was carried out using the product mass (M_i in Figure 3) as the basis. Since mixed biomass streams were considered in developing the model equations, subscripts x and y were used to denote two types of biomass materials used in the briquetting process, and b denotes the blend. The % proportion and density of biomass material x in mixture of x and y, was denoted with k_x and ρ_x respectively. The proportion of biomass material y (k_y) and density of biomass blend can be calculated as:

$$Proportion\ of\ biomass\ material\ y\ (k_y) = 1 - k_x$$

Equation 1

$$Density\ of\ biomass\ blend\ (\rho_{bd}) = k_x \cdot \rho_x + k_y \cdot \rho_y$$

Equation 2

The mass of biomass processed in a given unit is controlled by density of biomass material, the equipment volume and maximum allowable mass quoted by manufacturer. Since some of the equipment are designed to process specific feed biomass with density (ρ_b), a conditional criterion for selecting the density of new biomass material to be processed using the same equipment, is shown in Equation 3.

$$Actual\ density\ of\ biomass\ processed\ (\rho_d) = \begin{cases} \rho_{bd}\ if\ \rho_{bd} \leq \rho_b \\ \rho_b\ otherwise \end{cases}$$

Equation 3

The lower heating values (LHV) of biomass materials x and y, are used in Equation 4:

$$Heating\ value\ of\ biomass\ blend\ (LHV_b) = k_x \cdot LHV_x + k_y \cdot LHV_y$$

Equation 4

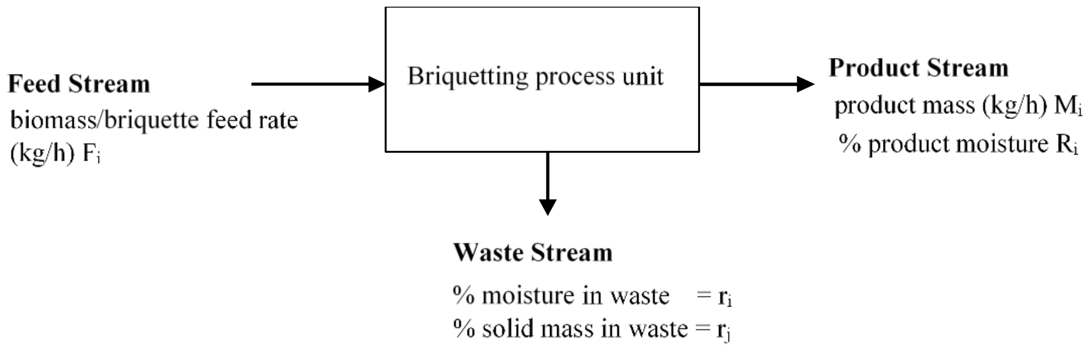

Figure 3: Mass balance representation for specific unit in briquetting system

Note: Please refer to mass balance diagram for definition of main symbols used in mass balance equations and other subsequent sections.

Product stream

The mass of moisture in the product can be calculated from Equation 5, while the solid mass can be calculated by substituting R_i with $(1 - R_i)$.

$$Moisture\ mass\ (\frac{kg}{h}) = R_i \cdot M_i$$

Equation 5

Waste stream

The moisture mass flow rate in the waste stream can be calculated using Equation 6, while R_i can also be substituted as $(1 - R_i)$ to calculate the solid mass in the waste stream.

$$Waste\ stream\ (Moisture\ mass) = \frac{r_i \cdot R_i \cdot M_i}{1 - r_i}$$

Equation 6

Feed stream

For the feed stream, Equation 5 and Equation 6 were used in developing Equation 7 for calculating the mass of moisture in the feed stream (Figure 3), and the mass of solid biomass can be calculated by replacing R_i with $(1 - R_i)$.

$$Feed\ stream\ (Moisture\ mass) = \frac{100\% \cdot R_i \cdot M_i}{1 - r_i}$$

Equation 7

Combining equations for moisture and solid mass in the feed stream gives Equation 8:

$$Total\ Feed\ (F_i) = M_i \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]$$

Equation 8

Note: The subscript "i" in the total feed (F_i) is denoted differently for each unit of the briquetting system, e.g., for storage unit, F_i is denoted as F_s.

The full model derivation for the subsequent units of the briquetting system is shown in Supplementary material S (6).

2.5 Life cycle impact assessment modelling

2.5.1 Energy indicators

The parameters calculated by the model to indicate the energy performance of the briquetting system, include: 1) Net energy production ratio (NER) which shows how much energy is produced as marketable products in comparison to the external, non-feed, energy input, 2) Energy return on investment (EROI) which represents the ratio of the energy delivered to energy used directly and indirectly in the process, and 3) the overall thermal efficiency (η_E)

which is the ratio of energy provided by a system to that supplied to it during thermal conversion [26]. The higher the EROI, the more commercially viable a biofuel is [27]. The EROI has also been used to examine the energy efficiency of some biofuels including bioethanol [28], and various fossil fuels [29]. The NER and EROI values greater than 1 are considered sustainable, thus 1 indicates a breakeven point.

2.5.2 Characterisation

The use of resources and emissions to the environment are collectively termed environmental burdens [6; 27]. Environmental impacts are a consequence of particular burdens. For example, SO_2 emission to the atmosphere is a burden, while the consequent acidification is an impact. Different impact assessment methods can be used to calculate the LCA results, the main difference is between the midpoint and endpoint which look at the different stages in the cause-effect chain to calculate the impact. The midpoint impact category (problem-oriented approach), translates impacts into environmental themes such as climate change and acidification, while the endpoint impact category (damage-oriented approach), translates environmental impacts into issues of concern such as human health, and natural resources. Endpoint results have a higher level of uncertainty compared to midpoint [14]. Therefore, a midpoint approach was employed in calculating the environmental impact of the briquetting system.

Environmental impact assessment initially starts by quantifying the burdens to the environment associated with emission of individual chemical species. These chemical species are further aggregated into environmentally functional groups referred to as Impact categories [10]. A generic equation for calculation of indicators for each impact category, using inventory data and generic characterisation factors, is shown in Equation 9 [28; 27].

$$\text{Category Indicator} = \sum_{s} (\text{Characterisation Factor}(s)\ X\ EmissionInventory(s))$$

Equation 9

Where s represents the chemical species, and the respective characterisation factors (specific contribution to the impact category) are available in the literature and databases.

The main impact categories used in this study included Global warming potential (GWP) (kg CO_2-eq), Acidification potential (AP) (kg SO_2-eq), Ozone layer depletion (ODP) (kg CFC-11-

eq), Human toxicity (HT) (kg 1,4-DB-eq) and Ecotoxicity (ET) (kg 1,4-DB-eq), obtained from the Recipe midpoint (H) methodology via the Simapro platform. These categories were considered based on their relevance on the briquetting unit [30], location of the briquetting plant, and previous work reported on LCA of biomass briquetting [29; 43]. For all the impact categories, key pollutants considered in the model, were based on a 1% cut off (The level of environmental significance associated with unit processes or product system that were excluded from the study) [21; ISO 14040].

2.6 User inputs

The first section of the user model includes a specific menu page which allows user to navigate easily within the model (Figure 4).

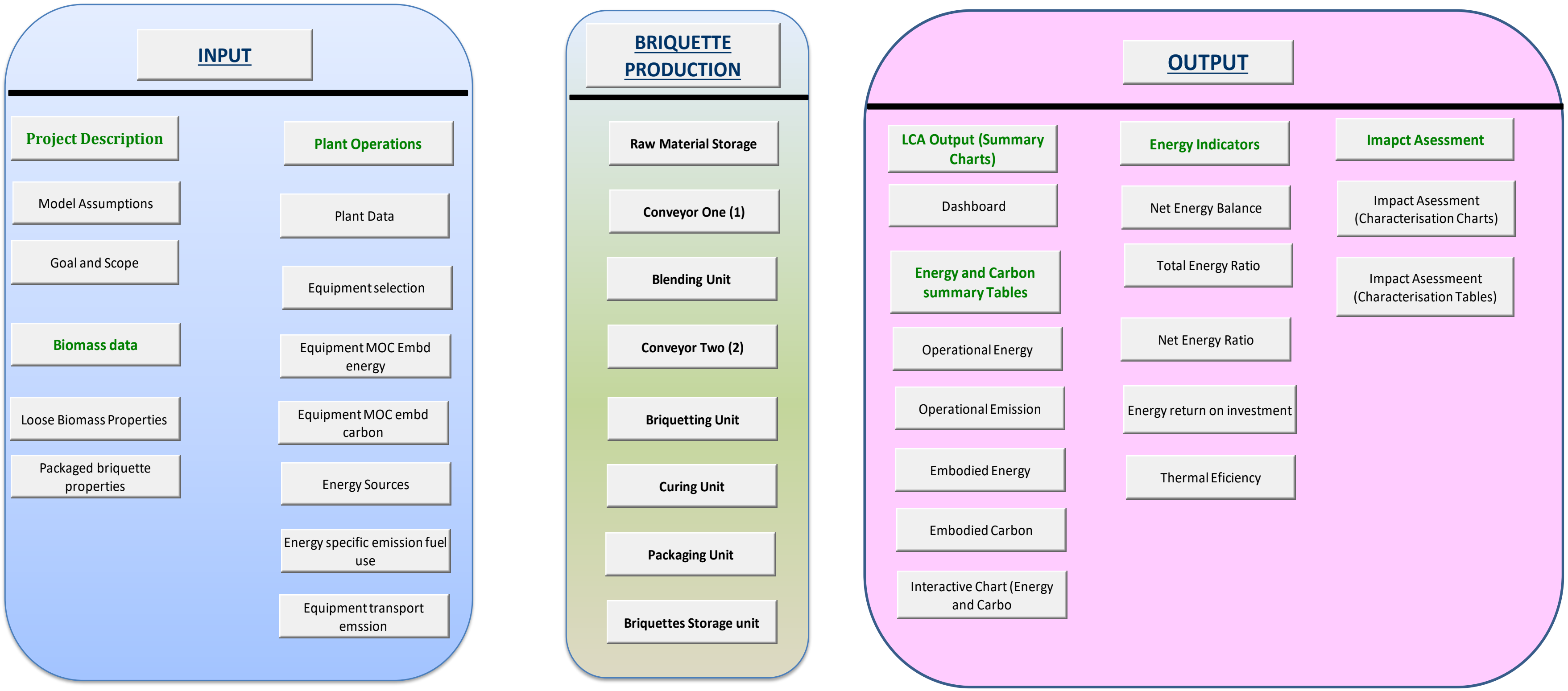

Figure 4: User navigation page in LCA model of fuel briquetting

The user input section allows the user to enter key briquetting process variables such as loose biomass density and moisture, scale of production, expected briquettes characteristics (e.g., density, moisture, shattering and abrasion index), and equipment selection, for up to ten scenarios. Figure 5 shows a screenshot of the user input tab. Other authors [e.g., 4;6] have used a similar approach in LCA modelling.

INPUT (VARIABLE)

NB!
USER MUST LEAVE CELLS BLANK FOR DEFAULT VALUES TO BE USED

USER DEFINED	DEFAULT BUT CAN BE CHANGED	DO NOT CHANGE

Back to Main Menu

UPDATE

RAW MATERIALS & BRIQUETTES PRODUCTION

Raw Materials Mixture	Unit	Default	User Defined							
Proportion of Rice husk in Mixture	%	-	100%	70%	60%	50%	40%	30%	20%	0%

Raw Material Properties	Unit	User Defined
Density of Rice husk	kg/m^3	354
Density of Corn cob	kg/m^3	278
Rice husk heating value (on dry basis)	MJ/kg	16.0
Corn cob heating value (on dry basis)	MJ/kg	18.0
Temperature	°C	25

Plant Operations	Unit	Default	User Defined
Proportion of Rice husk in Mixture	%	-	
Plant design Life	yrs	25.00	
Daily Operating hours	hrs	20.00	
Plant availbility per annum	%	80%	

Packaged Briquettes Properties	Unit	Default	User Defined							
Proportion of Rice husk in Mixture	%	-	100%	70%	60%	50%	40%	30%	20%	0%
Target Briquette Production	kg/day	60,000								
Product Moisture Content	%	7%	7%	9%	9%	10%	10%	10%	10%	10%
Product Temperature	°C	25.00								
Packaged Briquettes Bulk Bensity	kg/m^3	551.00	551.00	618.00	658.00	684.00	700.00	696.00	691.00	659.00
Fresh Briquettes Bulk Bensity	kg/m^3	686.00	686.00	751.00	777.00	787.00	788.00	796.00	793.00	792.00

EQUIPMENT SELECTION AND DETAILS

Equipment Selection	Unit	Default	User Defined							
Equipment	-	-	Feed Storage	Conveying 1	Blending	Conveying 2	Briquetting	Curing	Packaging	Storage
Selected Equipment Type	-	-	Steel-wal	AGICO-G	Ultra Feb	AGICO-G	LancaFue	GongyiLa	AGICO-TS	Steel-wal
Moisture Loss during use	%	0%						6%	7%	
Residue mass Loss during use	%	0%							7%	
Minimum Standby Equipment	%	25%								
Storage Requirement	days	2		-	-	-	-	-	-	
Equipment Transport Means	-	oceanic ship (GLO)								
Equipment Transport Distance	km	14,000								
Loading and Unloading time (Blending & Cu	mins	30	-	-		-	-		-	-
Allowance for Restriction Road Factor	%	20%								
Allowance Equipment Maintenance & Repairs	%	40%								

Figure 5: User input page for comparative LCA model of briquetting process

An "input model" tab is provided to also serve as an interface between the user input and main calculations. Based on user input, the input model searches the inventory for relevant equipment or material information required for subsequent calculations. However, the user has the option to override these pre-selected inventory values (also called default values).

2.7 Results section

The result section includes a series of chart and tables of various LCA output including energy and environmental impact (Figure 1, 2.1).

Charts representing a summary of the LCA results can be viewed from the "*Dashboard*" of the excel model (Figure 6), while other charts and tables can be accessed via the menu page. A screenshot of an interactive chart that allows the user to compare different LCA outputs is shown in Figure 7.

Figure 6: Dashboard for comparative LCA model of briquetting process

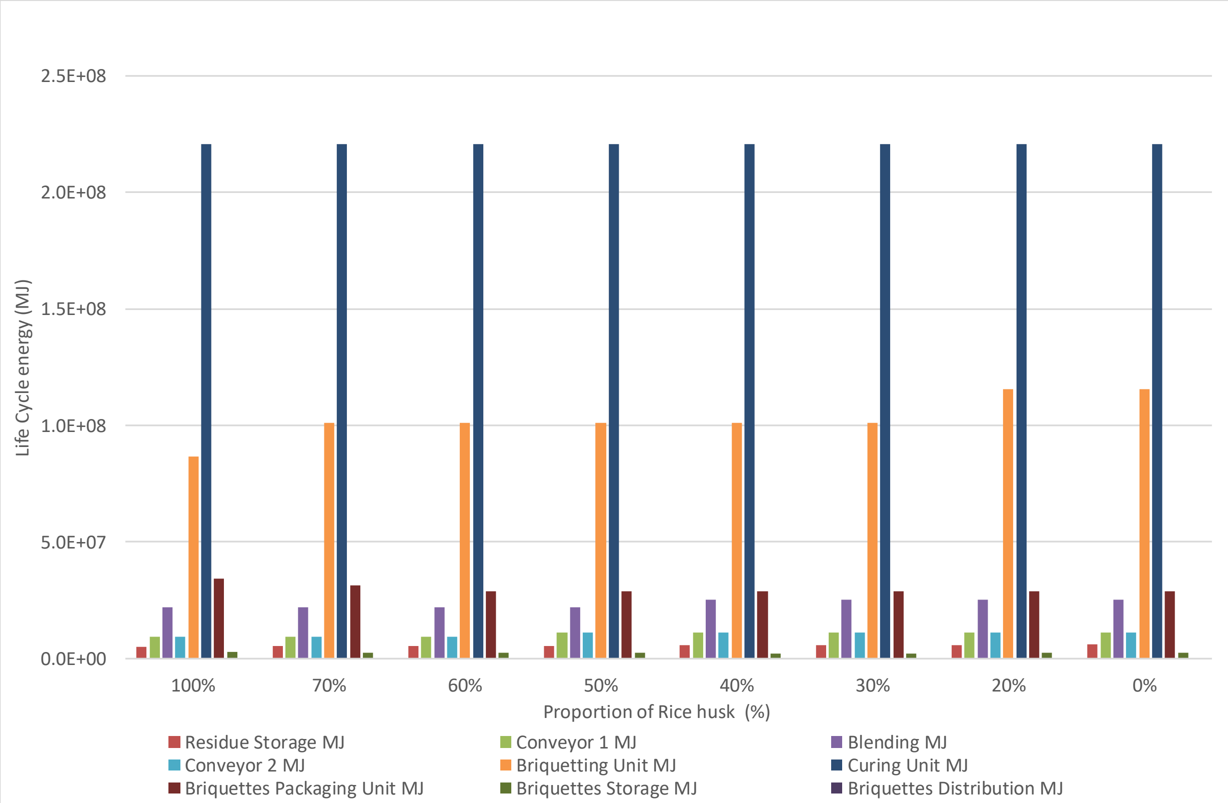

Figure 7: User interactive chart in comparative LCA model of briquetting process

3 Case study

3.1 Description

For the representative case study of briquetting of rice husks and corn cobs, a functional unit of 1 MJ briquette energy content at the briquetting plant gate was defined.

The life cycle scenario assumed the case of a fully operating briquette production plant located in the north central part of Nigeria with a packaged briquette production capacity of 20,000 t/year [Hu et al, 2014]. Briquette production was assumed to be carried out at 25 ± 2° C with a mass loss of 7% during briquette packaging i.e., average of shattering and abrasion resistance of fuel briquettes [19] and a 100% moisture loss (i.e., no solid loss) in curing unit. The shattering and abrasion resistance value excludes losses during briquette transport, but includes losses during the briquette packaging within the briquetting plant (from handling of packaged briquette, which was assumed to remain in the sealed bags through to conversion site).

A system boundary of gate-to-gate was used excluding the dryer and crusher (Figure 1) for the specific case study, because the case study focuses on identifying variations in environmental impact of briquetting different biomass with different properties, and the feed biomass used, was obtained with suitable moisture and particle sizes for briquetting.

3.2 Data source

The properties of loose rice husks and corn cobs biomass were obtained from Muazu & Stegemann [19]. Fuel briquettes were produced and characterised for blend ratios from 100% rice husks to 100 % corn cobs in the blends of rice husks and corn cobs.

The machinery used in the case study and its specific electricity consumption is shown in Table 1.

Table 1: Briquetting system machinery and building inventory (case study)

Briquetting unit machinery	Capacity (kg/h)*	Equipment Power rating (kWh)	Net weight (kg)	Main material of construction	Equipment code	Reference
Feed Storage	2	0.01	2700	Concrete	NA	[16,17]
Conveyor 1	550	2.0	130	Steel	GC-LXSSJ	[21]
Blender/mixer	991**	14.9	1000	Steel	SAI-DC10	[35]
Conveyor 2	550	2.0	130	Steel	GC-LXSSJ	[21]
Briquetting machine	550	27.5	2400	Steel	MPP550	[36]
Curing/cooling	3000	0.8	630	Steel	SKLN1.5; RBR 34-4	[34,35]
Packaging	550	5.0	60	Steel	TSP	[21]
Briquette Storage	2	0.01	2700	Concrete	NA	[16,17]

* storage unit in days
**calculated mass from volume given by manufacturer

3.3 Sensitivity analysis methods

As it is with many LCA model, among numerous data and assumptions used in the LCA model, 95 to 99% of the results may be determined by a few of these assumptions and/ data [14]. One of the proposed methods of testing the sensitivity of a LCA output to various input variables, is the factorial design [36,37].

Considering the comparative nature of the LCA model in this study, a sensitivity analysis was carried out within the model first by doing a "*contribution analysis*" of various input variables such as briquetting equipment, biomass/briquette density, moisture, abrasion resistance, and scale of production, used in the case study. A factorial design was employed to test the variable with the most effect to changes in the LCA result [38]. A high and low points for the input variables were selected based on the point at which significant changes were observed in the LCA output, from initial contribution analysis, variables with numerical input were varied by a factor of 3 (Table 2).

3.4 Results and Discussion

3.4.1 Life cycle energy and carbon dioxide emissions of rice husk and corn cob briquetting

Figure 8a and b show the percentage contribution of the different briquette production units to life cycle operational energy (MJ) of briquetting 100% rice husks, while Figure 9 shows the life cycle energy (operational and capital equipment) associated with the production of 1 MJ of fuel briquette energy from various blends of rice husks and corn cob biomass. Since the system boundary for the case study does not include biomass drying and crushing (3.1), the briquetting and blending units appear to be the most energy intensive units in the briquetting system. For example, 100% and 50% rice husks resulted in contributions of 39 and 42%, respectively, of the briquetting unit to the total life cycle operational energy. This is consistent with findings reported by other authors [e.g., Hu et al, [34] 63.2%, and Shie et al, [26]; 43.3%], for briquetting of corn stalk and rice straw respectively. The briquette curing unit had the least energy consumption of 0.43%, while fuel briquette storage had 0.5%.

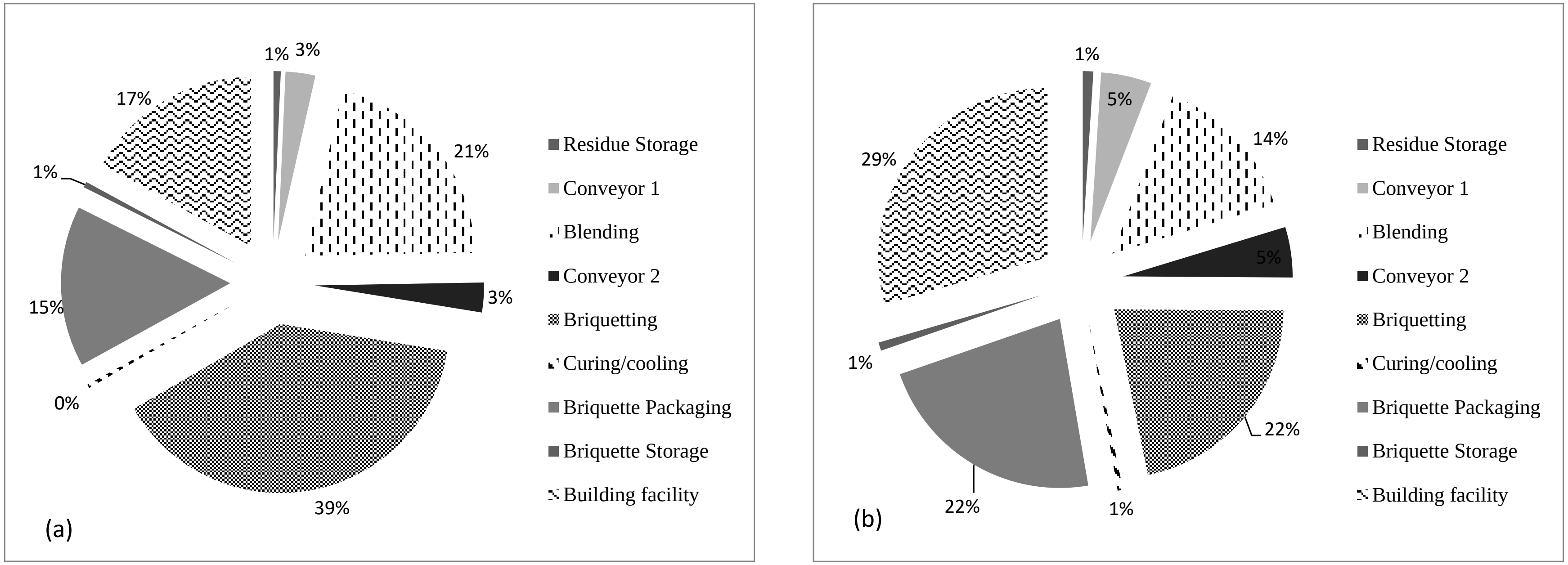

Figure 8: Life cycle operational energy of briquetting 100 % rice husks using briquetting equipment (a) T1 (LancaFuels-MPP550: low capacity, high energy consumption, high net weight) and (b) T2 (Lantian-LTM III: high capacity, high energy consumption, low net weight)

The contribution of each unit of the briquetting system to the life cycle energy, can be highly influenced by the type of equipment employed. For example, Figure 8a and b show the change in total life cycle energy of the different units of the briquetting system, as a result of change in the briquetting equipment employed. This can be attributed to factors such as the equipment design capacity and efficiency.

The use of higher ratio of corn cobs in the blend with rice husks, increased the overall life cycle energy of the system. This can be attributed to the lower density and morphological characteristics of corn cobs biomass, which reduced the number of biomass processing cycles per given time in the pre-densification units (i.e., before biomass compaction).

Figure 10 shows the life cycle carbon dioxide emissions of briquetting rice husks and corn cobs where the briquetting and blending units also had the highest contribution to the total life cycle carbon dioxide emissions. The life cycle energy (Figure 9) and carbon dioxide emissions (Figure 10) associated with production of 1 MJ fuel briquette energy content, were in the range of 0.2 to 0.3 MJ and 0.01 to 0.02 kg CO_2eq respectively, other authors reported similar values for 1 MJ of briquette energy, for example, Magelli et al [40] and Mani et al [41] reported values of 0.4 MJ and 0.02 MJ, and 0.02 kg CO_2eq and 0.012 kg CO_2eq respectively for wood pellets, while Li et al [39] reported 0.017kg CO_2eq for wheat straw pellets and Wang et al [42] also reported a value of 0.01 kgCO2eq for cornstalk briquette.

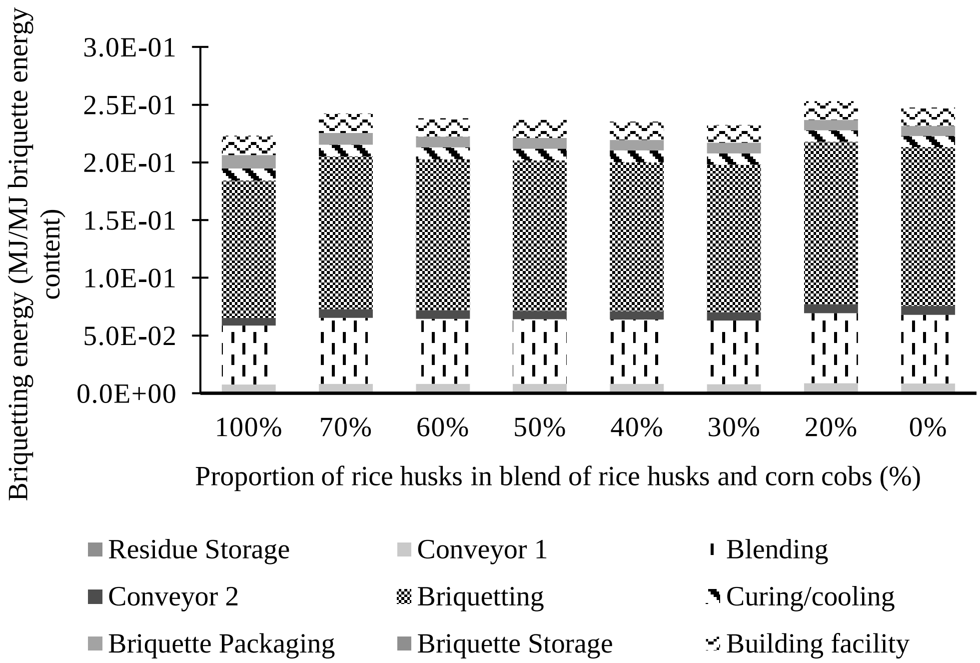

Figure 9: Life cycle energy of fuel briquetting with blends of rice husks and corn cobs

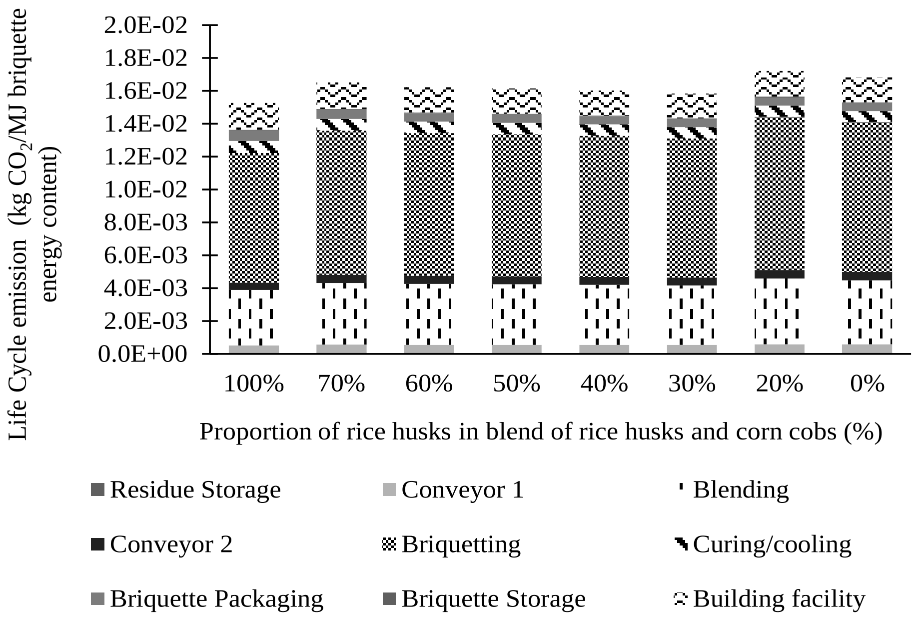

Figure 10: Life cycle carbon dioxide emissions of the fuel briquetting with blends of rice husks and corn cobs

A fair comparison between many LCA studies has been difficult because each assessment is specific to the design scenario. However, a fairly accurate comparison can be made among LCA results of different biomass or briquetting process, with the same functional unit, system boundary, and methodology.

3.4.2 Energy indicators for rice husks and corn cobs briquetting

Figure 11 shows the NER and EROI of the briquetting system. From Figure 11, the NER and EROI were both positive, and greater than 1, for all the blends of rice husks and corn cobs.

From Figure 11, the highest NER and EROI of 28 and 29, was obtained at 100% rice husks, this can be attributed to the low energy use for briquette production at 100 % rice husks compared with other blend ratios. However, the energy content of briquette was lowest at 100% rice husks and increased with higher blend of corn cobs, thus higher NER and EROI values of 27 and 28 was also obtained at 30/70 % blend of rice husks to corn cobs.

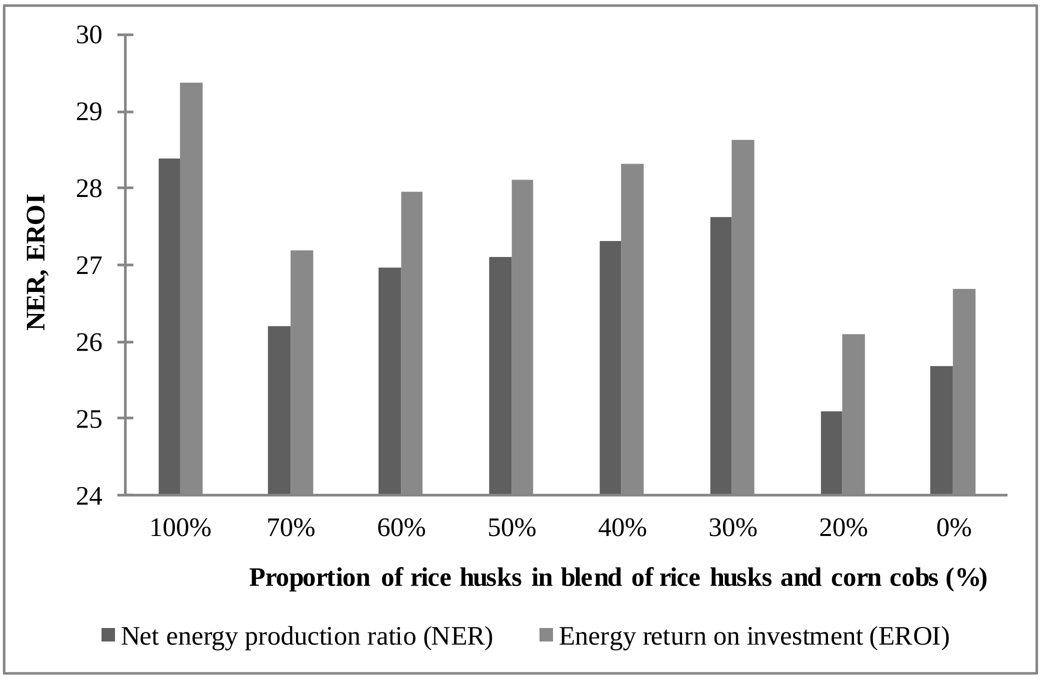

Figure 11: NER and EROI of fuel briquetting with blends of rice husks and corn cobs

3.4.3 Life cycle impact assessment

Figure 12 to Figure 16 shows the potential environmental impact of producing 1 MJ of fuel briquette energy content, for all the blends of rice husks and corn cobs. From Figure 12 to Figure 16, the biggest environmental impact of briquetting was on HT and GWP, and least impact on ODP. The large impact of briquetting on HT and GWP can be attributed to the high embodied impact of plant facilities, and impacts from operational and transport stages respectively. Findings by other authors [e.g.,42,43] also indicate high impact of briquetting on

GWP, and minimal impact on ODP [e.g., 43] in the briquetting of wood waste and mixed rice husks-glycerol respectively. Chiew & Shimada, [32] reported a GWP and HT with values of 43.74 kg CO_2-eq and 10 kg 1, 4-DB-eq respectively, from briquetting of 1 t of empty fruit bunches (EFB).

The main sources of the GWP include CO_2, CH_4 and N_2O emissions mainly from fossil fuel (e.g., diesel, coal) in operational use of the briquetting equipment, with CO_2 contributing over 80% to the total GWP [43].

The main contributors to HT include emissions of heavy metals such as zinc and nickel associated with primary production of briquetting equipment, and manganese during sea transportation of this equipment.

The environmental impact of producing rice husk and corn cob briquettes with 1 MJ energy content was in the range of 4.7E-2 to 5.1E-2 kg CO_2-eq for GWP, 6.6E-3 to 7.3E-3 kg SO_2-eq for AP, 1.3E-1 to 1.5E-1 kg 1,4-DB-eq for HT, 2.6E-8 to 2.8E-8 kg CFC-11-eq for ODP, and 2.8E-5 to 3.1E-5 kg 1,4-DB-eq for ET. LCA results are widely different [4], and the values obtained in this study fall within a realistic range of values 0.007 kg CO_2-eq for GWP and 0.01 kg 1, 4-DB-eq for HT obtained by some authors [32], but much lower than those obtained by other authors [e.g., 43] 0.08 kg CO_2eq.

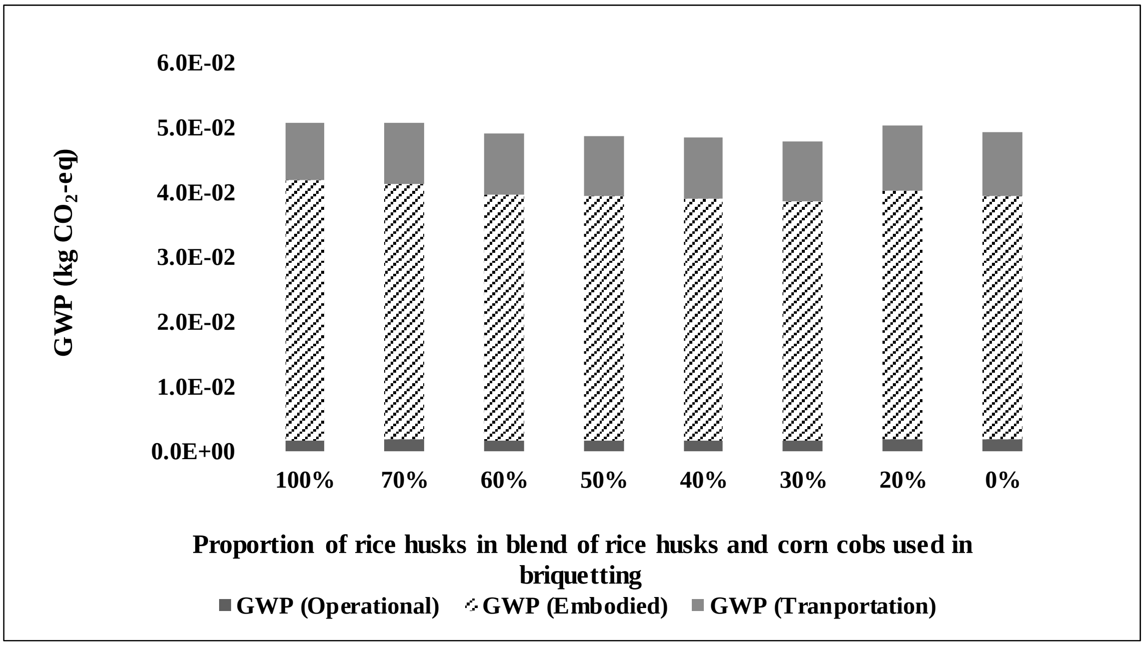

Figure 12: Life cycle Global warming potential (GWP) for briquetting various blends of rice husks and corn cobs biomass

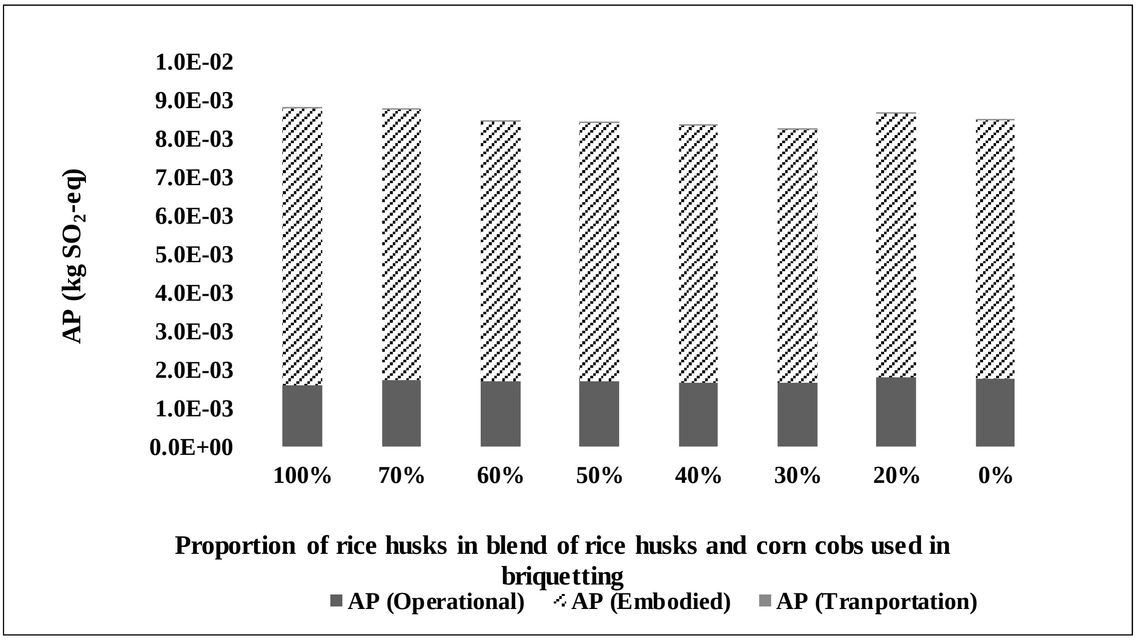

Figure 13: Life cycle Acidification potential (AP) for briquetting various blends of rice husks and corn cobs biomass

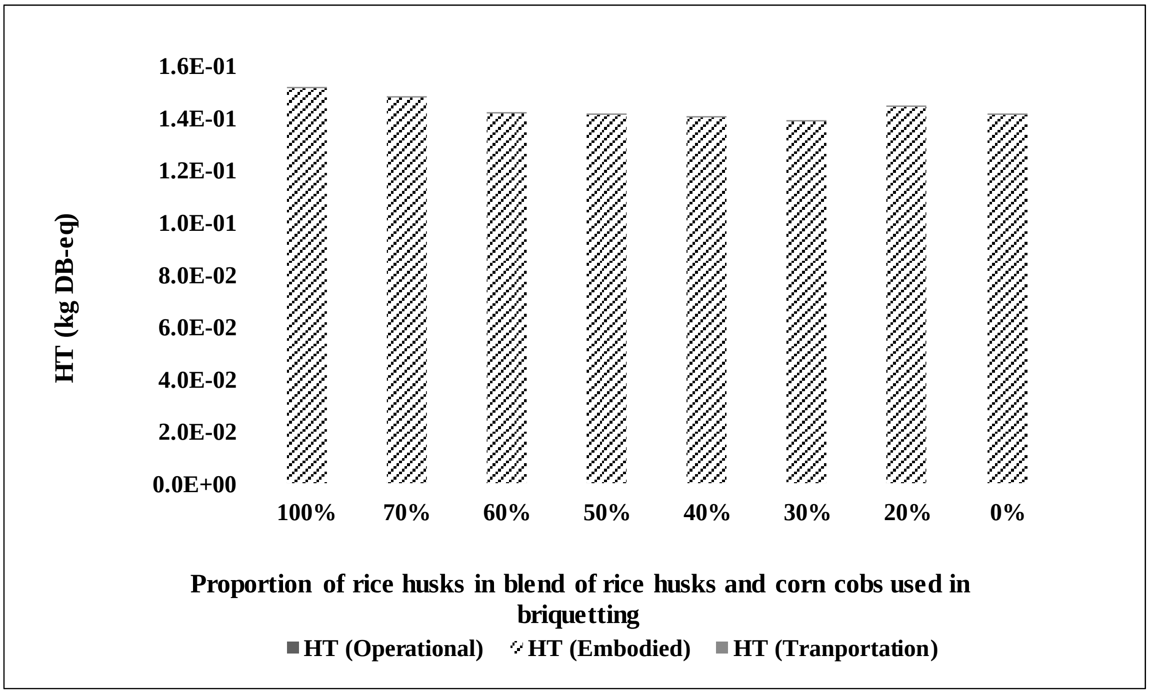

Figure 14: Life cycle Human toxicity (HT) for briquetting various blends of rice husks and corn cobs biomass

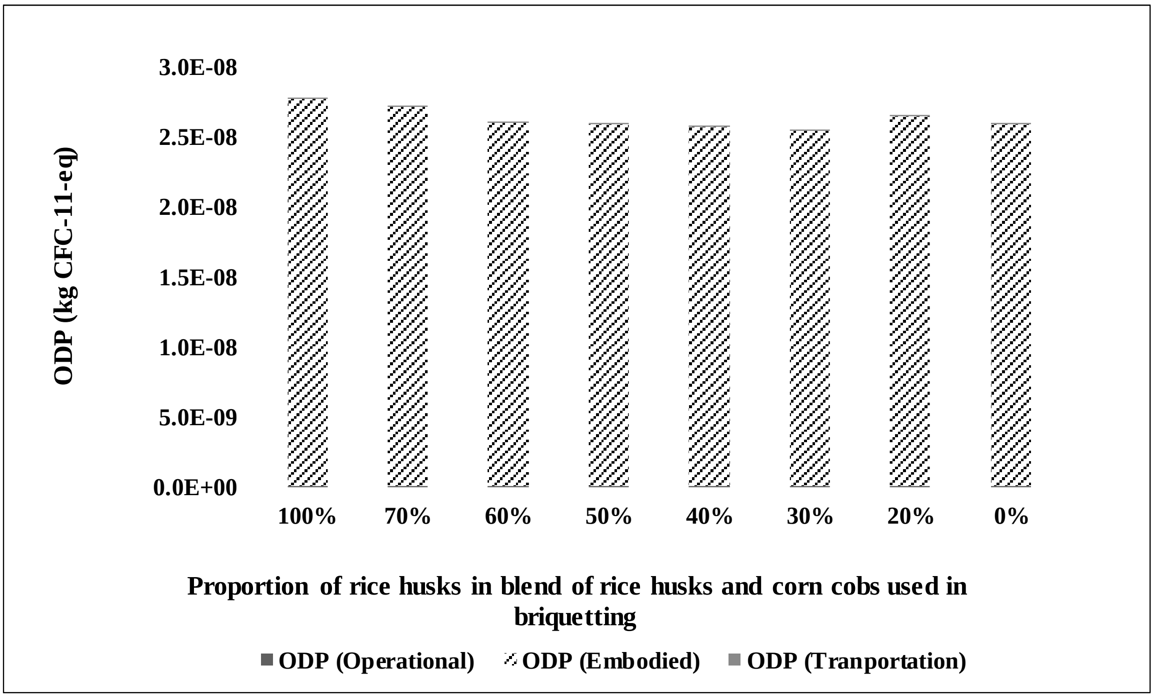

Figure 15: Life cycle Ozone layer depletion (ODP) for briquetting various blends of rice husks and corn cobs biomass

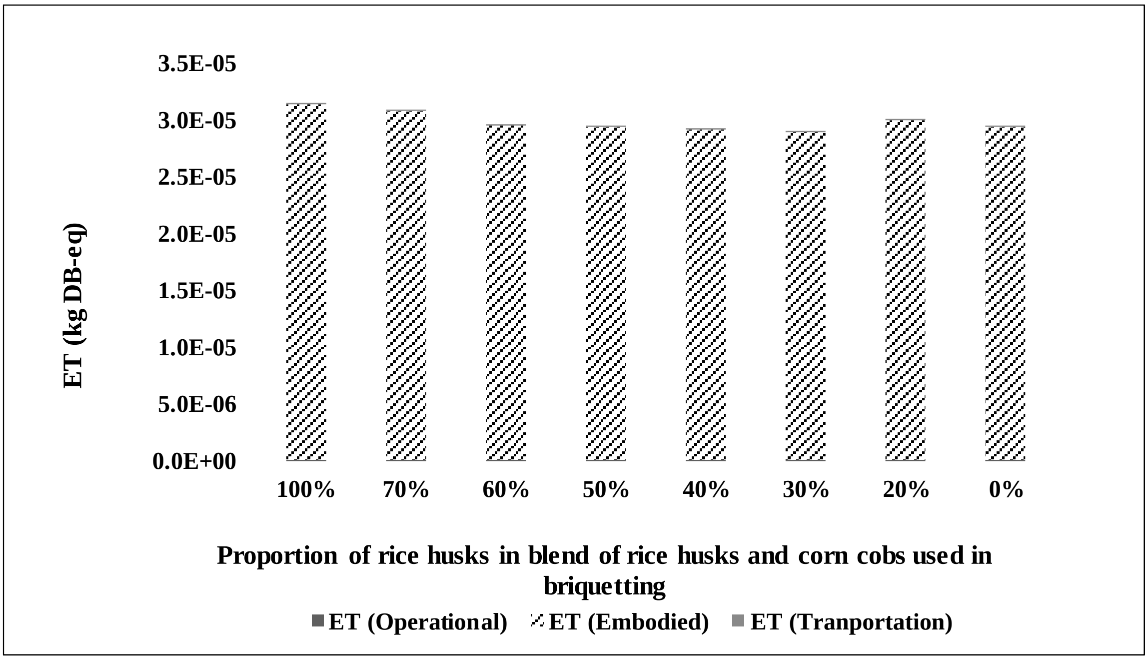

Figure 16: Life cycle Ecotoxicity (ET) for briquetting various blends of rice husks and corn cobs biomass

3.4.4 Sensitivity analysis

Table 2 show the results of sensitivity analysis carried out for briquetting with blends of rice husks and corn cobs. Columns 2 to 5 of Table 2 show the LCA input variables, and columns 6 to 9 of Table 2 show the LCA outputs. The main input parameters selected for the analysis include, (1 The variation in feed biomass properties and/ expected briquette density, denoted with (D), (2 The type of briquetting technology used, i.e., equipment design denoted with (T) (curing equipment A had higher capacity and lower energy consumption, and B had lower capacity and higher energy consumption), (3 The material of construction of principal building component, in the briquette production plant, denoted with (B), and 4)The change in briquette scale of production, denoted with (S).

Most LCA studies do not consider the problem of interaction for the purpose of simplicity, however, in reality, interaction within LCA calculation model and correlation among input parameters are main issues within the LCA process, which may result in inaccurate conclusion of the outcome [44]. The current model integrated various process variables and their interaction effects on the LCA, which provides a robust and transparent way of understanding the underlying causes of variations in the LCA outcomes. The main (individual) and interaction (two-factor and three-factor) effects of the LCA input parameters are further discussed.

Table 2: Sensitivity analysis results of LCA model of briquetting 100% rice husks

FACTORS					RESPONSES (units per MJ briquette energy content)			
S/NO	Biomass variability (variation in density (D) (kg/m3)	Briquetting Technology (Equipment type (T)*	Material for main building structure (B)	Scale of Production (S) (kg briquettes//day)	Total life cycle energy (MJ)	GWP ($kgCO_2$-eq)	Acidification potential ($kgSO_2$-eq)	Human toxicity (kg1,4,DB-eq)
1	354	B	concrete	20000	1.7E+00	1.5E-01	1.3E-02	2.7E-01
2	1062	B	concrete	60000	1.2E+00	1.0E-01	7.9E-03	1.6E-01
3	354	A	concrete	60000	2.2E-01	5.1E-02	7.2E-03	1.5E-01
4	1062	A	concrete	20000	2.5E-01	5.5E-02	7.8E-03	1.6E-01
5	354	B	steel	60000	1.6E+00	1.2E-01	5.3E-03	1.6E-01
6	1062	B	steel	20000	1.7E+00	1.3E-01	5.7E-03	1.7E-01
7	354	A	steel	20000	2.9E-01	5.4E-02	5.0E-03	1.5E-01
8	1062	A	steel	60000	2.3E-01	3.4E-02	2.8E-03	8.8E-02

*briquetting equipment A had lower capacity and lower energy consumption and B had higher capacity and higher energy consumption (MPP550; LTM6000)

*curing equipment A had higher capacity and lower energy, and B had lower capacity and higher energy consumption (LTM BOXDRY2t; LTM BOXDRY2.5t)

The use of briquetting equipment with lower capacity had a significant negative effect ($p<0.05$) on total life cycle energy and GWP, while its interaction with scale of production and biomass variability, had a positive effect on both energy and GWP. The technological differences in equipment design can have significant effect on the LCA result. For example, the use of counter flow cooler for briquette curing reduced the contribution of the curing unit to the total LCA result by a factor of 8, compared with a box dryer. This was attributed to the high equipment weight and longer residence time required using the box dryer.

The use of concrete building increased the impact of briquetting on energy and GWP of briquetting compared with steel building (Table 2), which can be associated to the differences in primary production of the materials of construction. Findings by Johnson [20], Guggemos & Horvath [45] and Bjorklund et al [37] indicated that concrete frame production had higher GWP (kg CO_2-eq) compared with steel, however, the recyclability of steel was not the main reason for this difference as reducing the recycled content of steel by 25% changed CO_2 emission by only 2.5%. The main cause of the higher CO_2 emission from concrete production was associated with the pyroprocesing stage.

The scale of production had small negative effect on energy and GWP, but its interaction with briquetting equipment had a significant positive effect on HT. Biomass variability yielded a significant positive main effect on HT, but had no apparent effect on the remaining indicators.

For all the variables included in the analysis, briquetting technology and scale of production show the most impact on the LCA output, which indicates a need for investigation to assess the uncertainty associated with these sources and improve the reliability of the LCA output.

3.5 General discussion

So far, existing LCA has been focused on other bioenergy processes such as the biomass cultivation stage (1). This model focuses specifically on the briquetting process and addresses common but important issues faced in many bioenergy processes such as wide variability in biomass feedstock and the differences in its various conversion processes [47; 48]. The LCA model can be used to improve the sustainability of an existing briquetting plant or guide towards development of more sustainable future briquetting systems.

The various measurements and data obtained in this study including materials, operational, equipment embodied and transport input variables, are all associated with errors. Data obtained from standard inventories had co-efficient of variations (CV) (ratio of standard deviation and the mean). The embodied energy and carbon of materials for equipment and buildings had CVs in the range of 0.3 to 27.3. Measurement of biomass raw materials and briquettes characteristics (e.g., density) had CVs in the range of 0.063 to 0.19 and 15 to 102 respectively. The errors associated with the overall briquetting LCA model (comprising of operational input parameters and emissions data) were between 8 to 15%, for changes in biomass variability, and up to 95%, for building and briquetting technology. There is need to improve on the accuracy and availability of data on briquetting equipment, as well as optimisation of the current briquetting technologies.

In terms of model accuracy and sensitivity, the complete accuracy of the briquetting LCA model is impacted by the high degree of uncertainty in the various components, however, the LCA model is fairly accurate for a comparative assessment of the briquetting system. The error associated with a comparative analysis is much connected between the scenarios, as such, the comparative differences are largely a consequence of differences between systems [10]. This means that the uncertainty is uniform across the model for all the cases.

3.5.1 Model limitations and future development

As it is with many models, there are limitations associated with the LCA model including;

1. Model doesn't combine two different transport means (e.g., road, rail) of briquetting plant equipment, for single assessment.
2. The model can only be used with two different biomass residues at a time or combined properties of many biomass materials into two main categories.

3. The ICE data within the model inventory can only be used for energy and carbon dioxide emissions assessment.
4. There is also a need to integrate sensitivity analysis tool into the model, as currently sensitivity analysis can only be carried out within the input page, on a separate tab within the model, or export to a separate software.
5. Future development of the model will include; improving and updating the current database and possible expansion of model scope by integrating upstream (agriculture) and downstream (thermal application) of briquette.

4 Conclusions

This study has developed a simple and comparative LCA model of briquetting process, and has demonstrated the significance of providing such model as a way of addressing current research gaps. The model was used in assessing the environmental impact of briquetting with blends of rice husks and corn cobs biomass, for up to 10 blend ratios.

Results showed that, for all the briquette production stages, the briquetting (densification) unit itself made the largest contribution to the total life cycle operational energy, with an input energy of 42% of the total life cycle operational energy. The total life cycle energy was in the range of 0.2 to 0.3 MJ/MJ fuel briquette energy content, indicating small influence of rice husks and corn cobs variability on the LCA results. For the same blend ratios, a total life cycle energy of briquetting in the range 0.2 to 1.7 MJ per MJ of fuel briquette energy content was also obtained with change in other LCA input parameters, in a sensitivity test.

A positive net energy balance was achieved for all the blends of rice husks and corn cobs, this had an energy return on investment (EROI) and net energy production ratio (NER) greater than 1.

The increase in ratio of rice husks in the blend with corn cobs increased the overall GWP, AP, HT, ODP, and ET of the briquetting system but reduced the life cycle energy (MJ/MJ briquette energy) requirement of the system. For the same listed impact categories, the 30/70 % ratio of rice husks to corn cobs had the lowest environmental impact.

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Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication.

Glossary

M_i = unit target mass output (kg/h)

F_i = unit mass feed rate (kg/h)

M_e = Design equipment capacity (kg/h)

R_i = product moisture content (%)

r_i = moisture loss during processing (%)

r_j = solid mass loss during processing (%)

E_i = total calculated unit energy consumption

E_e = equipment energy consumption

V_i = maximum allowable volume (m^3) of equipment (mold in briquetting machine and space in curing)

ρ_b = vendor quoted residue density (kg/m^3)

ρ_r = density ratio (kg/m^3)

ρ_{bd} = density of biomass blend (e.g., x + y)

ρ_d = final calculated density used (kg/m^3)

N_i = calculated number of equipment

W_e = weight of equipment (kg)

E_{ee} = equipment embodied energy (MJ/kg)

T_r = total briquette curing time (h)

T_{op} = total operating time (h)

T_s = total storage time in requirement (h)

H_s = height of storage building (m)

k_x = proportion biomass material A in blend of A and B

k_y = proportion biomass material B in blend of A and B

ρ_x = density of biomass material A (kg/m^3)

ρ_y = density of biomass material B (kg/m^3)

C_p = specific heat capacity (J/kgk)

T_c = product temperature (^oC)

LHV = lower heating value of biomass (MJ/kg)

HV_i = product heating value (MJ/kg)

Xi = fraction of various material of construction (e.g., steel, plastic) (%)

Yi = specific embodied energy factor (MJ/kg)

s = spacing between equipment and building wall

x = Base length of individual equipment

y = width of individual equipment

d1 = vehicle allowance at building entry

d2 = rear allowance for access/maintenance

t = building wall thickness

n = number of equipment within building

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6 Supplementary materials

6.1 Model derivations for subsequent units of the briquetting system

The general assumptions employed in developing the life cycle energy equations for the various briquetting process units are shown below;

- A simple warehouse building was assumed to house both the onsite storage of loose biomass and briquette.
- Equipment are operated in batch mode.

- Storage unit operational energy is limited to electric bulbs and extractor fans.
- The model is valid for storage of 100% of each material storage and subsequent material blending ratios can be calculated from the derived equations.
- Equipment data were obtained from manufacturer and used in developing subsequent equations.
- Number of batches per hour is a controlling criterion, and manufacturer equipment production rate was used.
- The time for feeding of biomass to and out of the equipment is included in the manufacturer equipment hourly production rate.
- The manufacturer equipment capacity shown excludes allowance for any losses.
- A batch mixer with a volume (Vm) is constraint by a maximum allowable mass (Mlm), therefore, the number of batches mixed per hour is dictated by either volume of the mixer or the maximum allowable mass of residue that can be loaded to mixer at a given time.
- Blended residue is mixed continuously for a given time (tm), which includes the time for loading, mixing and emptying of the mixer.
- Equipment maintenance and repairs were accounted for, by allocation of additional percentage mass of each equipment weight.
- Equipment installation energy at briquetting site was not included.

The total operational energy in each unit was denoted as E_i (the subscript "i" also changes for each unit, e.g., the subscript "i" is substituted by "s" for storage unit), the equipment power rating (e.g., kWh) was denoted with E_e, and equipment production capacity with M_e.

For all the briquetting process units, all equipment data obtained from the manufacturers were referred to as VENDOR or BASE data.

Mixed streams of biomass were considered in developing the life cycle model equations for all units apart from biomass drying and crushing, where separate streams of each biomass were considered. A detailed model calculation for these units was not provided, however, a space within the model has been created for users to input their own values of energy and emissions specific to these units, for integration into the overall model results page.

6.1.1 Loose biomass/briquette storage

Total storage feed can be calculated from Equation 10 substituting F_i from Equation 8.

$$Total\ storage\ feed\ (F_{st}) = M_s \cdot T_s \cdot T_{sd} \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right]$$

Equation 10

T_s and T_{sd} represents daily operating time (h/d) and buffer storage duration (d) respectively. The total area required for storage can be calculated using Equation 11.

$$Total\ storage\ unit\ area\ (A_{st}) = \frac{V_{st}}{H_s}$$

Equation 11

where H_s is the height of storage facility, and V_{st} the total volume of storage required by various biomass materials in the blend, based on their densities (ρ_i) and % proportion, as shown in Equation 12.

$$Total\ storage\ volume\ (V_{st}) = \sum_{i=A}^{n} \frac{M_i}{\rho_i}$$

Equation 12

Given $M_i = K_i \cdot F_{ts}$, the total energy required for biomass or briquette storage from biomass materials x and y, can be calculated using Equation 13.

$$Storage\ unit\ energy\ (E_s) = E_e \cdot \frac{V_{st}}{H_s} = \frac{E_e}{H_s} \cdot F_{ts} \cdot \left[\frac{K_A}{\rho_A} + \frac{K_B}{\rho_B}\right]$$

Equation 13

Where E_e is the equipment power rating (kW).

6.1.2 Conveyor

The total number of batches per given time (1h) can be calculated from Equation 14, and Equation 15 can be used to calculate the number of conveyors required for a given mass of biomass or briquette per time.

$$Number\ of\ batches\ (N_{lc}) = \frac{F_c}{M_{ld}}$$

Equation 14

$$Total\ number\ of\ conveyors\ required\ (N_c) = \frac{N_{lc}}{N_L}$$

Equation 15

Where F_c is the total feed mass and M_{ld} is the maximum mass that can be loaded on the conveyor per given time. N_L is the maximum number of batches that can be achieved per time (h) based on equipment design, which can be calculated from equipment capacity and volume, and biomass material or briquette density. Therefore, the total energy required to convey a given mass of biomass/briquette can be calculated using Equation 16.

$$Conveyor\ unit\ energy\ (E_c) = E_e \cdot \frac{F_c}{M_e} \cdot \frac{\rho_b}{\rho_{bd}}$$

Equation 16

Me is the manufacturer-quoted equipment capacity (kg/h).

Substituting F_c (Equation 8, 2.4.1) into Equation 16 and applying a density and mass constraint within the conveyor specification will give Equation 17 and Equation 18.

$$Conveyor\ unit\ energy\ (E_c) = E_e \cdot M_r \cdot \rho_r \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]$$

Equation 17

M_r is the ratio of design equipment capacity (M_e) and production target (M_t), and ρ_r is the ratio of manufacturer quoted biomass density (ρ_b) and calculated biomass density (ρ_{bd}).

$$M_r = \frac{M_i}{M_e} \qquad\qquad \rho_r = \frac{\rho_b}{\rho_{bd}}$$

$$Conveyor\ unit\ energy\ (E_c) = E_e \cdot M_r \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right]$$

Equation 18

Note:

Equations 17, 21b, 25b, 28a, 31b: applicable when feed biomass density equals to or less than manufacturer quoted biomass density.

Equations 18, 21c, 25c, 28b, 31c: applicable when biomass density equals to or greater than Manufacturer quoted biomass density.

6.1.3 Blending/mixing

The number of a specific batch mixed per given time, can be determined using Equation 19.

$$Number\ of\ batch\ mixed\ (N_{lm}) = \frac{F_m}{M_{lm}}$$

Equation 19

M_{lm} is the calculated mass of biomass that will fit in a mixer, based on mixer volume (V_m) and density of biomass blend (ρ_d), and F_m is the total feed mass for mixer.

This can be further used to calculate the equipment required for blending of the total feed biomass (F_m) (Equation 20).

$$Number\ of\ mixers\ required\ (N_m) = \frac{N_{lm}}{N_{bm}}$$

Equation 20

Where N_{bm} is the number of batches per hour per mixer, this means that for a specific time (t_m) given to mix the total feed biomass (F_m), the number of batches that was calculated based on biomass properties and volume of mixer (V_m), is also constrained by the maximum allowable volume and mass of mixer for a given time (t_m). Therefore, the energy required for blending of multiple feeds, can be calculated using Equation 21a.

$$Blending\ energy\ (E_m) = E_e \cdot N_m$$

Equation 21a

and by substituting N_m, equation 21a becomes 21b.

$$Blending\ energy\ (E_m) = \frac{E_e \cdot t_m}{V_m \cdot \rho_d} \cdot F_m$$

Equation 21b

By substituting F_m, Equation 21b will become 21c, depending on the ratio of vendor quoted biomass density (ρ_b) and the calculated density of biomass blend (ρ_{bd}), see Note in 6.1.2.

$$Blending\ energy\ (E_m) = M_i \cdot \left[\frac{E_e \cdot t_m}{V_m \cdot \rho_b} \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]\right]$$

Equation 21c

6.1.4 Briquetting

In a typical briquetting machine, the mold is filled with specific mass of biomass material (M_{die}) before compaction. This can be calculated using Equation 22, and the total number of times a mold can be loaded per hour, can then be calculated using Equation 23.

$$Mass\ of\ biomass\ to\ fill\ briquetting\ mold/die\ (M_{die}) = V_{die} \cdot \rho_d$$

Equation 22

$$Total\ number\ of\ mold\ loading\ (N_{ldie}) = \frac{F_{bq}}{M_{die}}$$

Equation 23

V_{die} is the volume of mold, and F_{bq} is the total briquetting feed biomass.

Therefore, the number of units of equipment required to densify a given mass of biomass per hour, can be determined using Equation 24.

$$Total\ number\ of\ briquetting\ machine\ required\ (N_{bq}) = \frac{N_{ldie}}{N_{ld}}$$

Equation 24

N_{ld} is the number of time the briquette compaction mold can be loaded per time (h) based on manufacturer equipment design, and N_{ldie} is the calculated (new) number times the mold can be loaded based on individual biomass properties.

Equation 25a can be used to calculate the total energy required for briquetting.

$$Briquetting\ energy\ (E_{bq}) = E_e \cdot \frac{F_{bq}}{M_e} \cdot \frac{\rho_b}{\rho_{bd}}$$

Equation 25a

By further expansion of F_{bq}, we have Equations 25b and 25c (see Note in 6.1.2).).

$$Briquetting\ energy\ (E_{bq}) = E_e \cdot M_r \cdot \rho_r \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right]$$

Equation 25b

$$Briquetting\ energy\ (E_{bq}) = E_e \cdot M_r \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right]$$

Equation 25c

see Equation 17 for M_r and ρ_r.

6.1.5 Briquette curing/cooling

The number of curing cycles for fresh briquettes per equipment within a given time (e.g., day) can be calculated using Equation 26, while Equation 27 can be used to determine the equipment required.

$$Number\ of\ briquette\ curing\ cycles\ (N_{rc}) = \frac{F_r}{M_{lr}}$$

Equation 26

$$Number\ of\ briquette\ curing\ machine\ required\ (\ N_r\ ) = N_e \cdot T_r$$

Equation 27

Where M_{lr} is mass of loading per curing equipment/space, T_r is the manufacturer quoted residence time for briquettes in machine, while N_e is the ratio of calculated number of curing cycles N_{rc} to the manufacturer quoted curing cycles per equipment per time N_{rd} , F_r is the total curing unit feed.

Thus, the total energy required to cure fresh briquette can be calculated using Equation 28a and/or 28b.

$$Briquette\ curing\ energy\ (E_r) = \frac{E_e}{(V_r \cdot \rho_{bd})} \cdot M_i \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right] \cdot \frac{T_r^2}{T_{op}}$$

Equation 28a

$$Briquette\ curing\ energy\ (E_r) = \frac{E_e}{(V_r \cdot \rho_b)} \cdot M_i \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right] \cdot \frac{T_r^2}{T_{op}}$$

Equation 28b

Where V_r and T_{op} represents volume of curing space in equipment and daily operating hours respectively.

See Equation 3 for ρ_{bd} and ρ_b.

6.1.6 Briquette packaging

The total number of packaged briquette bags per hour per equipment can be calculated using Equation 29. Therefore, based on the calculated number of bags, the equipment required to package a given mass of cured/cooled briquettes can be calculated from Equation 30.

$$Number\ of\ packaged\ briquette\ bags\ (N_{pb}) = \frac{F_p}{M_{lp}}$$

Equation 29

Where M_{lp} is the calculated mass of briquettes per bag and F_p is the total packaging unit feed of briquettes.

$$Number\ of\ packaging\ machines\ required\ (N_p) = \frac{N_{pb}}{N_{lp}}$$

Equation 30

Where N_{lp} is the vendor quoted packaging capacity (e.g., bags per hour).

The total energy required for briquetting of loose biomass can be calculated using Equation 31a.

$$Briquette\ packaging\ energy\ (E_p) = E_e \cdot \frac{F_p}{M_e} \cdot \frac{\rho_b}{\rho_{bd}}$$

Equation 31a

see Equation 3 for ρ_{bd} and ρ_b.

Equation 31a was further expanded and modified (using density variation in feed biomass and change in production target) to give 31b and 31c (see Note in 6.1.2).

$$Briquette\ packaging\ energy\ (E_p) = E_e \cdot M_r \cdot \rho_r \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right]$$

Equation 31b

$$Briquette\ packaging\ energy\ (E_p) = E_e \cdot M_r \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right]$$

Equation 31c

See Equation 17 for M_r and ρ_r,

6.1.7 Embodied energy

Machinery

A generic Equation 32 can be used to calculate embodied energy of machinery used in all units of the gate-to-gate briquetting system.

$$Equipment\ embodied\ energy\ (E_{ei}) = N_e \cdot W_e \sum_{i=1}^{n} X_i \cdot Y_i$$

Equation 32

N_e which stands for actual number of equipment required/used in a specific unit, varies for the different units of the briquetting system. For example, briquetting equipment embodied energy (E_{eb}) was determined from Equation 33.

W_e is the net weight of equipment, X_i is the fraction of each material of construction of the equipment e.g., steel (%), and Y_i is the unit embodied energy of each material (MJ/kg).

$$Briquetting\ equipment\ embodied\ energy\ (E_{eb}) = \frac{N_{ldie}}{N_{ld}} \cdot W_e \sum_{i=1}^{n} X_i \cdot Y_i$$

Equation 33

Buildings

The building space requirement of each equipment was calculated from the base dimensions of the individual equipment, allowing space for vehicle access, maintenance and allowance at rear, all in metres (m) as shown in Figure 17. In writing the equation for calculating the specific burden of the briquetting plant building, the building technical specification (including type of structure and specific features) and material inventory (e.g., steel, concrete, wood), while some careful assumptions were employed where necessary (e.g., use of length, height and width in building).

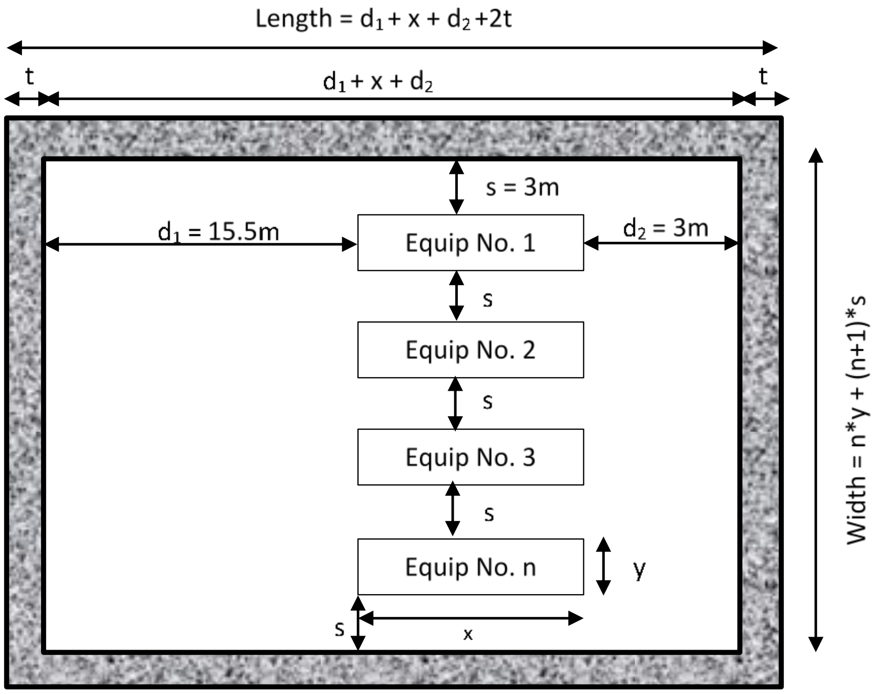

Figure 17: Approach used in calculating building space requirement of individual equipment in the briquetting plant

6.1.8 Fuel briquette energy content

The product (e.g., briquette) heating value (HV_i) can be determined using Equation 34, which can be used to calculate the life cycle energy per MJ of briquette energy.

$$Briquette\ heating\ value\ (HV_{bq}) = M_i \cdot (1 - R_i) \cdot LHV_b + M_i \cdot R_i \cdot C_p \cdot T_p$$

Equation 34

Where C_p is the specific heat capacity (MJ/kgK) of water, T_p is the product temperature.

6.1.9 LCA model pages – Briquetting process inventory

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Conveyor | Packaging Unit
Blending Unit | Curing Unit
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S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Ratio of total surface area for Construction/demolition to floor area	Energy Consumption	Total Weight per Equipment	Operating Temperature	Product Temperature	Net Weight per Equipment	Floor Dimension (Length)	Floor Dimension (Width)	Ratio of total surface area to floor area/maintenance	Equipment BASE Area	Building Construction energy	Building Maintenance energy	Building Demolition enrgy	Refe enc
-	-	-	-	-	kg/m^3	kg/hr	m2/m2	kWh	kg/Equip	°C	°C	kg/m2			m2/m2	m2	MJ/m2	MJ/m2	MJ/m2	
1	Storage Unit	Steel-walls	BLD-0	Steel-walls-BLD-0(2kg/hr)	354	2	3.61	0.0086	1383821	25	25	4070	34	10	6.58	340	39.48	31.6	12.15	
2	Storage Unit	Concrete-walls	BLD-1	Concrete-walls-BLD-1(2kg/hr)	354	2	3.61	0.0086	950921	25	25	2797	34	10	6.58	340	36.72	31.6	11.4	
3	Storage Unit																			
4	Storage Unit																			
5	Storage Unit																			

S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Dummy Column 2	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area
-	-	-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C		m	m	m	m2
1	Conveyor Unit	AGICO	GC-LXSSJ	AGICO-GC-LXSSJ(550kg/hr)	354	550	1.6	2	130	25	25		4.3	0.56	0.5	3.6
2	Conveyor Unit	AGICO	GC-PDSSJ	AGICO-GC-PDSSJ(600kg/hr)	354	600	1.7	3	120	25	25		2.11	0.91	0.7	2.9
3	Conveyor Unit															
4	Conveyor Unit															

S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Mixing time	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area
		-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C	mins				m2
1	Blending Unit	Ultra Febtech	DCM	Ultra Febtech-DCM(531kg/hr)	354	531	1.5	6	2500	25	25	20	33	4	2	173
2	Blending Unit	Tapasya ENG	SAI-DC10	Tapasya ENG-SAI-DC10(991.2	354	991.2	2.8	14.91	1000	25	25	10	4	5	3	28
3	Blending Unit															
4	Blending Unit															
5	Blending Unit															

S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Dummy Column 2	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area
		-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C					m2
1	Briquetting Unit	LancaFuels	MPP550	LancaFuels-MPP550(550kg/hr	354	550	3.42119E-05	27.5	2400	25	25		2.5	1.73	1.5	6.4875
2	Briquetting Unit	AGICO	GC-MBP-500	AGICO-GC-MBP-500(500kg/hr	354	500	1.25664E-05	35	4000	25	25		3.2	1.5	1.5	7.2
3	Briquetting Unit	AGICO	GC-MBP-1000	AGICO-GC-MBP-1000(800kg/h	354	800	7.85398E-05	45	7000	25	25		2.5	1.74	2.04	6.525
4	Briquetting Unit	Lantian	LTM-6000	Lantian- LTM-6000(2800kg/hr	170	2800	3.42119E-05	45	3800	25	25		3	1.96	1.2	8.82
5	Briquetting Unit	Lantian	LTM	Lantian-LTM(3000kg/hr)	354	3000	2.01062E-06	18.5	300	25	25					
6	Briquetting Unit	GEMCO	GC-HBP125	GEMCO-GC-HBP125(1000kg/hr	210	1000	0.000153938	9	1200	25	25					
7	Briquetting Unit	AGICO	GCBA-I	AGICO-GCBA-I(210kg/hr)	354	210	3.63168E-05	21	585	25	25					
8	Briquetting Unit	AGICO	GCBA-II	AGICO-GCBA-II(350kg/hr)	354	350	7.85398E-05	31	1300	25	25					
9	Briquetting Unit	AGICO	GCBC-I	AGICO-GCBC-I(210kg/hr)	354	210	0.000435802	19.4	700	25	25					
10	Briquetting Unit	AGICO	GCBC-II	AGICO-GCBC-II(350kg/hr)	354	350	0.000760265	22.9	1000	25	25					
11	Briquetting Unit	AGICO	GC-HBP60	AGICO-GC-HBP60(60kg/hr)	354	60	3.42119E-05	5.5	650	25	25					
12	Briquetting Unit	AGICO	GC-HBP125	AGICO-GC-HBP125(125kg/hr)	354	125	3.42119E-05	7.5	1100	25	25					
13	Briquetting Unit	AGICO	GC-HBP250	AGICO-GC-HBP250(250kg/hr)	354	250	3.42119E-05	11	2800	25	25					
14	Briquetting Unit	AGICO	GC-HBP350	AGICO-GC-HBP350(350kg/hr)	354	350	3.42119E-05	22	3500	25	25					
15	Briquetting Unit	AGICO	GC-HBP500	AGICO-GC-HBP500(500kg/hr)	354	500	3.42119E-05	37	4200	25	25					
16	Briquetting Unit	AGICO	GC-HBP1000	AGICO-GC-HBP1000(1000kg/hr	354	1000	3.42119E-05	55	6000	25	25					
17	Briquetting Unit	LancaFuels	MPP550	LancaFuels-MPP550(500kg/hr)	354	500	0.000201062	27.5	2400	25	25					
18	Briquetting Unit	LancaFuels	MPP60	LancaFuels-MPP60(60kg/hr)	354	60	7.85398E-05	5.5	680	25	25					
19	Briquetting Unit	LancaFuels	MPP180	LancaFuels-MPP180(180kg/hr)	354	180	0.000153938	9.2	1200	25	25					
20	Briquetting Unit	LancaFuels	MPP350	LancaFuels-MPP350(350kg/hr)	354	350	0.000153938	27.5	2200	25	25					

S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Curing Cycle	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area
		-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C	hrs	m	m	m	m2
1	Curing Unit	GongyiLan1	BOXDRY-2t	GongyiLan1-BOXDRY-2t(2000k	1200	2000	1.6	35	5443	105	25	7	5.8	2.2	2	19.14
2	Curing Unit	GongyiLan	BOXDRY-2.5t	GongyiLan-BOXDRY-2.5t(2500	1200	2500	1.5	2.95	6000	105	25	5	5.8	2.2	2	19.14
3	Curing Unit	AZS	Counterflow SKLN1.5	AZS-Counterflow SKLN1.5(300	1200	3000	1.5	0.75	634	30	25	0.5	1.1	1.3	3.2	2.145
4	Curing Unit	AZS	Counterflow SKLN2.5	AZS-Counterflow SKLN2.5(500	1200	5000	2.5	0.75	680	30	25	0.5	5.8	2.2	2	19.14

S/N	TYPE	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Mass per bag	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area
		-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C	kg	cm	cm	cm	m2
1	Packaging Unit	AGICO	TSP	AGICO-TSP(550kg/hr)	1200	550	0.004	5	60	25	25	5	12	5.2	6.3	62.4
2	Packaging Unit	HGELGOOG	GG402	HGELGOOG-GG402(550kg/hr)	1000	550	0.005	5	50	25	25	5	1.2	0.52	0.63	0.624