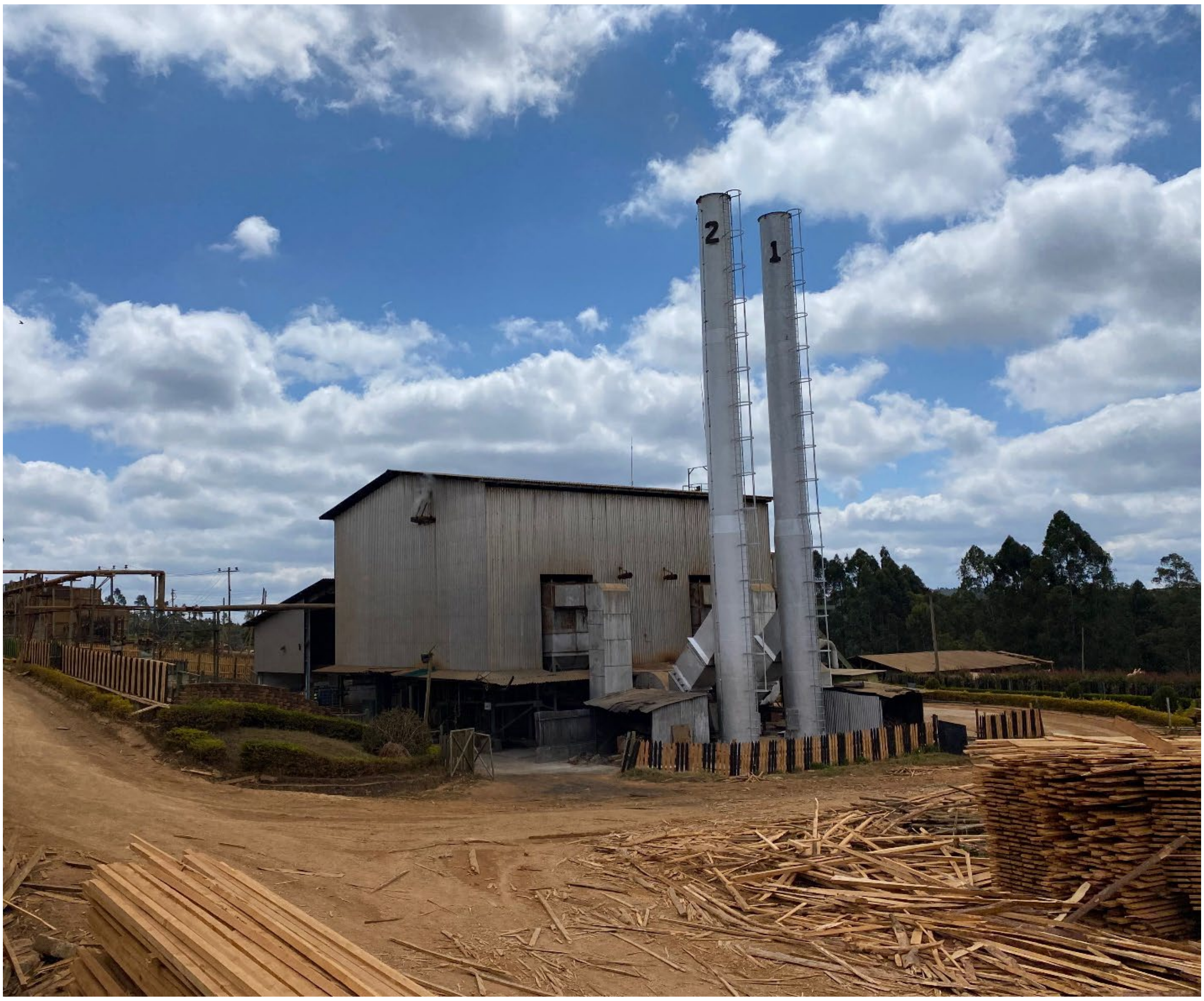

Bioenergy for Sustainable Local Energy Services and Energy Access in Africa

Bioenergy Mass-Energy Balance Model Methodology document

FOREIGN, COMMONWEALTH AND DEVELOPMENT OFFICE

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About the BSEAA2 Programme

BSEAA is a two-year research programme intended to identify and support the development of innovative, commercial bioenergy pathways and technologies that will accelerate the successful production and use of bioenergy in Sub-Saharan Africa (SSA), with a focus on ten countries: Ethiopia, Ghana, Kenya, Mozambique, Nigeria, Rwanda, South Africa, Tanzania, Uganda and Zambia. The research aims to identify and investigate commercially viable opportunities for the development of modern bioenergy technologies for electricity and/or heat generation in the output range 10 kWe to 5 MWe, with a Technology Readiness Level of 5+. BSEAA targets bioenergy entrepreneurs (particularly technology and project developers), investors and policymakers, to catalyse action for bioenergy development in SSA.

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Cover photo: Combined heat and power plant at Tanganyika Wattle Company, Njombe, Tanzania. Credit: Emmanuel Michael Biririza.

INTRODUCTION

A Mass-Energy Balance model was developed by Aston University as part of the 'Bioenergy for Sustainable Local Energy Services and Energy Access in Africa - Phase 2' (BSEAA2) project, funded by the UK Foreign, Commonwealth and Development Office (FCDO) as part of the TEA programme. The model forms a part of a suite of research tools and products developed under BSEAA2 to enable project developers, practitioners, investors and other stakeholders to make decisions regarding the technical and commercial viability of investing in bioenergy technology within seven shortlisted industries, referred to as 'demand sectors'. These demand sectors (DS) and their associated bioenergy pathways and focus countries are presented in Table 1. Detailed reports for each demand sector are available here.

Table 1. Shortlisted demand sectors for BSEAA2 research

<table>
<tr><th>No.</th><th>Demand sector</th><th>Biomass resource</th><th>Technology</th><th>Country</th></tr>
<tr><td>1</td><td>Cement manufacturing</td><td>Biomass residues, part-replacing fossil fuel</td><td rowspan="2">Combustion for heat</td><td>Nigeria</td></tr>
<tr><td>2</td><td>Tea processing</td><td>Biomass briquettes, part-replacing fuelwood</td><td>Kenya</td></tr>
<tr><td>3</td><td>Wood processing</td><td>Wood processing residues</td><td>Combustion for CHP[1]</td><td>Tanzania</td></tr>
<tr><td>4</td><td>Palm oil processing</td><td>Palm oil mill effluent</td><td rowspan="3">AD[2] for CHP</td><td>Ghana</td></tr>
<tr><td>5</td><td>Horticulture</td><td>Fruit & vegetable processing residues</td><td>Kenya</td></tr>
<tr><td>6</td><td>Dairy</td><td>Cattle manure</td><td>South Africa</td></tr>
<tr><td>7</td><td>Sisal processing</td><td>Sisal processing residues</td><td>AD for electricity</td><td>Kenya</td></tr>
</table>

Based on the known feedstock types and properties, and the expected plant capacity and performance, the model quantifies mass and energy flows and outputs of energy in form of heat and/or power under optimised performance conditions.

The process units within each DS are modelled as "black boxes". The processes taking place within each unit are simplified to mathematical relationships based on referenced and validated performance and efficiency data. By defining the input conditions, the user obtains values about the performance of the process for each DS. The process routes are represented by a simplified block diagram for each DS. The model allows the user to carry out "virtual experiments", by adjusting the input variables based on their particular interests.

The model has been designed to be used as a scoping tool and not a detailed process simulation. Therefore, there is a level of uncertainty in the accuracy of the model. Based on the quality of the data and the level of detail, the team anticipate the uncertainty level to be +/-30%.

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[1] CHP - Combined heat and power.

[2] AD – Anaerobic digestion is the conversion of organic material by micro-organisms in the absence of oxygen into biogas and digestate.

The user selects the feedstocks for each DS, the target capacity in MW (either thermal, electrical or both) and the capacity factor[3].

MODEL ASSUMPTIONS

Feedstock composition

The user can view feedstock characteristics on the "Feedstocks" tab of the model, which details the moisture content, ash content, volatile matter, fixed carbon, lower heating value (LHV) and higher heating value (HHV) for a representative range of feedstocks. Based on the feedstock(s) chosen by the user for each pathway, the model automatically selects the relevant feedstock properties for the calculations. For each DS, up to two different feedstocks can be selected. By defining the feedstock blending proportions, the model generates the average properties for the feedstock mix.

DS1 – Cement production

In the cement industry, coal, petroleum coal (petcoke) or natural gas are currently the most common fossil fuels used to produce clinker in various countries. The user can model the mass and energy balances for partial substitution of these fossil fuels, selecting different types of biomass feedstock. The model also allows the user to select the type of cement manufacturing process, i.e. wet, dry (1-stage) or dry (multi-stage), which determines the energy required to produce clinker. Further, the model allows the user to specify the percentage of fossil fuel energy being replaced by energy from biomass.

The steps involved in the calculations are as follows:

- The target capacity defines how much energy will be provided by the fossil fuel and the biomass to produce clinker, e.g. with a target value of 5MW and a 50% fossil fuel substitution rate, 2.5MW will be provided by the biomass feedstock(s).
- The model calculates how much fossil fuel (Table 2) and how much biomass is required to meet the target capacity.

Table 2 - Assumed fossil fuel composition[4,5]

Parameter	Coal	Petcoke	Natural gas
Moisture content, wt%	9	3	0
LHV, MJ/kg	26	33	50
Ash content, wt%	9.9	1	0

- The process type defines the energy demand per kg of clinker (see Table 3). The energy demand figure is used to calculate how much clinker will be produced.

[3] Capacity factor is the ratio of the actual energy output over time compared to the maximum possible energy output.
[4] TNO. (2021). Phyllis2—Database for the physico-chemical composition of (treated) lignocellulosic biomass, micro- and macroalgae, various feedstocks for biogas production and biochar. https://phyllis.nl/
[5] Department for Business, Energy & Industrial Strategy (2020). Digest of UK Energy Statistics (DUKES): calorific values.

Table 3 - Energy demand per kg of clinker[6]

Type of process	Energy demand per kg clinker, MJ/kg
Dry (multi-stage)[7]	3.4
Dry (single stage)	4.5
Wet	6.06

- Based on the clinker produced and the assumed composition (Table 4), the model calculates the components required (limestone, gypsum, silica and others). The silica levels are adjusted by adding clay (see Table 5), and the calcium oxide requirement is adjusted by adding limestone to the reactor.

Table 4 – Assumed clinker composition[8]

Compound	Weight %
CaO	68.0
SiO_2	22.1
Al_2O_3	5.9
Fe_2O_3	4.1

Table 5 - Assumed clay composition[9]

Compound	Weight %
SiO_2	63.3
Al_2O_3	23.5
Fe_2O_3	5.4
CaO	1.3

- The amount of air required to burn the biomass and fossil fuel is then calculated, assuming a 15% excess of oxygen to ensure complete combustion. This step also calculates the amount of flue gas produced.
- The capacity factor specified by the user is used to calculate the annual biomass and fossil fuel requirement and cement production.

DS2 – Tea processing

Thermal energy is used in the processing of black tea for withering and drying of the fresh leaves. For this demand sector, the user can model the replacement of fuel-wood[10] with biomass alternatives such as biomass briquettes and loose agri-residues. The model user can specify the fuelwood substitution level.

The steps involved in the calculations are as follows:

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[6] IEA (2020), Cement, IEA, Paris https://www.iea.org/reports/cement
[7] The dry multi-stage process is a common industry standard
[8] IEA (2020), Cement, IEA, Paris https://www.iea.org/reports/cement
[9] van Dongen BE, Fraser SE, Insoll T. The composition and origin of Ghana medicine clays. Anthropol Med. 2011;18(2):285-302. doi:10.1080/13648470.2011.591204
[10] Fuelwood: A solid biofuel originating from woody biomass, where the original composition of the wood is preserved (FAO, 2004a).

- The process purpose defines how the energy is utilised and how much tea may be processed (see Table 2). The assumed energy split is 35% for withering and 65% for drying.[11]

Table 2 - Tea processing energy requirements (agreed by project consortium)[12]

Type of process	Thermal energy usage, MJ/kg of made tea
Withering	6.6
Drying	12.4
Withering and drying	19

- For withering, a steam pressure of 4 bar and 90°C is required, while for drying, higher pressure steam is required at 10 bar and 150°C.
- The boiler efficiency assumed for turning the feedstocks into usable heat is 80%, i.e. 80% of the energy contained within the fuel is turned into heat energy in the form of steam.
- Based on the composition of the feedstock(s) and the substitution level of fuelwood, the LHV is defined. This is used to calculate how much alternative biomass and fuelwood is required to meet the target capacity. The assumed properties of the fuelwood are given in Table 3.

Table 3 – Assumed fuelwood properties[13]

Parameter	Weight %
Moisture content	25
Ash content	3
Volatile matter	83
LHV (MJ/kg)	13

- The amount of air required to burn the feedstocks is then calculated, assuming a 15% excess of oxygen to ensure complete combustion. This also defines the amount of flue gas produced.
- The capacity factor specified by the user is used to calculate the annual fuel requirement (alternative biomass and fuelwood), heat generation and made tea output.

DS3 – Wood processing

The residues produced during wood processing can be used to produce heat, to generate power or (in a CHP plant) to generate both heat and power. The target plant capacity, capacity factor and type of feedstock(s) defined by the user, enable the amount of biomass required to be calculated.

The steps involved in the calculations are as follows:

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[11] GIZ, KTDA, Ethical Tea Partnership, & Strathmore University. (2019). Thermal Manual [Training manual for plant technicians, mechanics and boiler operators]. https://www.ethicalteapartnership.org/wp-content/uploads/2019/09/Thermal-Training-manual-new.pdf

[12] GIZ, KTDA, Ethical Tea Partnership, & Strathmore University. (2019). Thermal Manual [Training manual for plant technicians, mechanics and boiler operators]

[13] TNO. (2021). Phyllis2—Database for the physico-chemical composition of (treated) lignocellulosic biomass, micro- and macroalgae, various feedstocks for biogas production and biochar. https://phyllis.nl/

- The biomass properties are established based on the feedstock(s) chosen by the user. This defines the LHV (in MJ/kg) and is used to calculate the amount of biomass required to meet the target capacity.
- Based on the process choice, the assumed system efficiencies for energy conversion are taken from Table 4. These efficiencies are used in DS 3-7.

Table 4 – Assumed energy conversion efficiency for DS3-7[14]

Process	Electrical efficiency	Thermal efficiency
CHP	15%	65%
Electricity only	30%	n/a
Heat only	n/a	80%

- The amount of steam generated varies according to the process choice. To use steam in a steam turbine in the CHP and electricity-only scenario, superheated steam is required. The steam property requirements were based on a 3 MW steam turbine[15]. For the heat only scenario, lower grade steam is acceptable. The steam properties used are shown in Table 5.

Table 5 – Steam properties

Process choice	Steam pressure, bar	Steam temperature, °C
CHP, electricity only	41	302
Heat only	10	190

- The amount of air to burn the feedstocks is then calculated, assuming a 15% excess of oxygen to ensure complete combustion. This defines the amount of flue gas produced.
- The solid residue (ash) is calculated based on the ash content of the chosen feedstocks.
- The capacity factor is used to calculate the annual figures for heat and/or power generation.

DS4 – DS7 (Palm Oil Processing, Horticulture, Dairy, Sisal Processing)

In the palm oil processing, horticulture, dairy and sisal processing sectors (DS4-7), the model is configured for biogas[16] production. The biogas generated can be utilised to generate heat, power or combined heat and power. The feedstocks available vary according to the DS under consideration. Based on a target energy capacity defined by the user, the amount of biomass required is calculated.

The steps involved in the calculations are as follows:

- Using the LHV of methane (CH_4) and the assumed energy conversion efficiency values in Table 4, depending on the process choice, the amount of methane required to meet the target capacity is calculated.

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14 Abu-Ebid M, et al. (2015). Review of the Reference Values for High-Efficiency Cogeneration, European Commission.
15 US Department of Energy (2016). Steam Turbines Technology Description Combined Heat and Power Technology Fact Sheet Series
16 Biogas is a mixture of gases produced by the breakdown of organic matter in the absence of oxygen (anaerobically), primarily consisting of methane and carbon dioxide.

- The Buswell equation[17] (below) back-calculates the amount of biomass required to produce the methane and gives the theoretical biogas composition, which changes depending on the feedstock. This equation also determines whether any additional water is required in the anaerobic digestor for the reactions to proceed.

Buswell equation:

$$C_cH_hO_oN_nS_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2O$$
$$\rightarrow \frac{1}{8}(4c - h + 2o + 3n + 2s)CO_2 + \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + 2NH_3 + sH_2S)$$

- The carbon conversion efficiency for AD is set at 60%[18] and is used in combination with the value obtained from the Buswell equation to calculate the quantity of biomass required to obtain the target energy capacity.
- It is assumed that an anaerobic digestor operates at 35°C. The ambient temperature set by the user is used to calculate if any additional heat is required to bring the biomass feedstock within the digester up to this operational temperature. The input temperature is limited to 35°C as higher ambient temperatures are unlikely.
- **Please note**, that the model does not consider the design of any heat exchangers to preheat the biomass or the source of the energy to provide this heat. i.e. it does not impact the biomass input values. The heat value is provided for information only to align with the LCC work.
- There are mesophilic and thermophilic digesters that have different operating temperature requirements. The model does not consider these differences as a more generalised approach was taken, but in case of an operational temperature above 35°C, this will have an impact on the heat input required for the process.
- The amount of steam generated varies according to the process choice. To use steam in a steam turbine in the CHP plant and electricity-only scenarios, superheated steam is required. The steam property requirements were based on a 3 MW steam turbine[15]. For the heat-only scenario, lower grade steam is acceptable. The steam properties used are shown in Table 5.
- In the case of the use of a gas turbine or gas engine for electricity generation, no steam is produced.
- Depending on the process choice, the amount of air to burn the biogas is calculated, assuming a 15% excess of oxygen to ensure complete combustion. This defines the amount of flue gas produced.
- The capacity factor is used to calculate the annual figure for heat and/or power generation.

[17] Banks, C. (2011). Anaerobic digestion and energy, University of Southampton.
[18] Banks, C. (2011). Anaerobic digestion and energy, University of Southampton.