DEVELOPMENT OF A TECHNICAL AND ECONOMIC FEASIBILITY STUDY FOR ANAEROBIC DIGESTION OF THE ORGANIC FRACTION OF SOLID WASTE FROM HOUSEHOLDS, HOTELS AND MARKETS IN MAURITIUS

OUTPUT 5: SCHEMATIC DESIGN OF THE BIOGAS PLANT

Submitted to:

Climate Technology Centre & Network (CTCN)

Department of Environment, Ministry of Environment, Solid Waste Management & Climate Change, Republic of Mauritius

Solid Waste Management Division, Ministry of Environment, Solid Waste Management & Climate Change, Republic of Mauritius

Submitted by:

Council for Scientific and Industrial Research (CSIR)

University of Mauritius (UoM)

Technical Assistance Ref. No.: 2020000014
Budget line:

Issue: v1.0

Date: 17 December 2021

Contents

Acronyms

AD	Anaerobic Digestion
BMP	Biochemical Methane Potential
CHP	Combined Heat and Power
FW	Food Waste
FSMY	Full Scale Methane Yield
MD	Methane degradability
MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
TBMP	Theoretical Biochemical Methane Potential
TS	Total Solids
VS	Volatile Solids
WtE	Waste to Energy
YW	Yard Waste
TKN	Total Kjedahl Nitrogen

Overview of Deliverable 5

This output documents the design, mass, and energy balance of the proposed 100 tons/day anaerobic digestion facility. This output used the information from the 2 previous deliverables as input for the design. Design of plant focused on the process flow diagram, isometric diagrams and sizing of some of the units in the plant. The mass and energy balance calculated the material and energy flows within the plant. A list of equipment and building that are required is provided. The latter part of the document focuses on requirements and opportunities for integration of the biogas plant into the existing organic waste value chain and the energy and digestate supply chains while also considering the aspects of gender and youth.

1 Introduction

Deliverable 3 of the Technical Assistance provided an indication of the biogas and electricity production potential of organic wastes generated in Mauritius while Deliverable 4 recommended the most suitable technology for Mauritius while also proposing a possible siting location for the biogas plant. Based on the outputs of Deliverables 3 and 4 and considering a biogas plant of capacity 100 tonnes per day, a schematic design of the biogas plant is presented in Deliverable 5, together with the required equipment constituting the biogas plant. A material and energy flow diagram is also presented wherein all quantities of different streams are provided. Finally, Deliverable 5 concludes with some of the requirements and opportunities for integration of anaerobic digestion into the existing value and supply chain with a consideration of the gender and youth aspects.

2 Development of a schematic design and inventory of the biogas plant (Deliverable 5.1)

2.1 Development of a schematic design of the biogas plant

2.1.1 Process description

The biogas plant is designed to treat 100 tons/day of the OFMSW coming from households, market and hotels through a source-separated collection system. The design of biogas plants depends mostly on the type and amount of substrate supplied. A biogas plant consists of several units. Figure 1 shows the various processing steps involved in biogas production. The received bagged organic waste (FW and YW) will first be channelled to the bag opener unit, where the bags carrying the waste will be ripped open to release the OFMSW contained within. The OFMSW will then be sent to the physical pre-treatment unit (S-101) to remove any unwanted materials that may be present in the waste but not suitable for anaerobic digestion. The pre-treated waste is then stored in storage tank(T-101) prior to be loaded into the anaerobic digester(R-101). The OFMSW will be conveyed into the digester using a screw pump(C-103) into digester. This feed will be dosed with sodium hydroxide solution contained in the dosing unit (D-101) to maintain the pH at near neutral acidity. This unit operate when the pH in the reactor drops below 6.8. It will mixed with recirculated digestate at a ratio of 1:6 fresh feed to the digestate (De Baere, 2010). Furthermore, it will mixed with low temperature steam to raise the temperature of the feedstock and maintain that of digester contents at 55 ^{o}C. In the digester, the OFMSW will anaerobically digested to produce biogas and digestate. The biogas will be collected at the top and stored temporarily in the biogas storage tank (T-102) prior to use in the cogeneration plant. The biogas will pass through the moisture removal unit (H-101) prior to its use in the gas engine (G-101) for generation of electricity. The exhaust fumes from the turbine will be channelled to the shell and tube heat exchanger (H-102) for waste heat recovery. Low pressure steam will be generated from the waste heat, this steam will be used to heat and maintain the temperature of the digester content in the thermophilic temperature regime. The digestate will be dewatered in the filter press (F-101) prior to it been sent to the composting facility.

2.1.1.1 Substrate receiving unit

The efficient transport and supply of substrate is critical for the proper operation of the biogas plant. The present feasibility study concentrates on solid organic waste from hotels, fresh produce markets, and household. Apart from wastes from the south and south-east, all these wastes pass via one of the five transfer stations before being disposed of at the landfill., The transfer stations, and the landfill (for the south and south-east) might be called waste generating points. A weighbridge will be located at the entrance of the facility to weigh the exact amount of organic wastes entering the facility.

2.1.1.2 Physical pre-treatment

The primary goal of physical pre-treatment is to improve feedstock digestibility, meet sanitary requirements, and boost biogas yield. Physical pre-treatment stage entails:

- Sorting and separating undesirable material from feedstock.

This is an important and necessary first step in sorting and separating impurities and undesirable materials from the feedstock substrate. The solid organic waste from hotels, fresh produce markets, and household contains stones, sand and other physical impurities. In the case of sand, these impurities are normally separated by sedimentation in storage tanks, and they must be periodically cleaned from the bottom of the tanks. Before pumping the substrate into the equipped main storage tank, a pre-tank with particular grills that can keep stones and other physical impurities could be used.

- Crushing

The purpose of crushing feedstock material is to prepare particle surfaces for biological degradation and subsequent methane generation. In general, the breakdown process accelerates as the size of the object decreases. Particle size reduction can be achieved biologically and/or mechanically.

2.1.1.3 Storage of substrate/Pre-treated OFMSW storage tank

The primary goal of substrate storage is to adjust for seasonal variations in substrate availability. It also allows for the mixing of several co-substrates for continuous digester feeding. The type of storage is determined by the substrate. Bunker silos for solid substrate (e.g. food stock) and storage tanks for liquid feedstock are the two basic types of stores (e.g. slurries and liquid manure). Bunker silos can keep substrate for up to a year, whereas storage tanks may store it for a few days to months. Delivery intervals, quantities to be stored, and daily amounts fed into the digester all influence the size of the storage facilities. In this case, bunker silos for solid substrate is recommended.

2.1.1.4 Feeding System

After storage and pre-treatment of substrate, it is fed into the digester. There are two categories of substrate, pumpable and non-pumpable. The pumpable substrate category includes liquid organic wastes and animal slurries (e.g. flotation sludge, fish oil, cattle wastes). Feedstock types which are non-pumpable (e. g. fibrous materials, maize silage, grass, manure with high straw content) can be poured by a loader into the feeding system and then fed into the digester by use of a screw pipe system.

2.1.1.5 Pumps

The pumpable substrate is transferred from the pre-treated storage tank to the digesters using pumps. Centrifugal pumps and positive displacement pumps are the two most common types of pumps. Centrifugal pumps are frequently submerged, although they can also be installed in a dry shaft alongside the digesters. Positive displacement pumps, as opposed to centrifugal pumps, are more pressure resistant. They are self-sucking, work in two directions, and can reach high pressures despite having a limited conveying capacity. Centrifugal pumps, on the other hand, are more commonly chosen than positive displacement pumps due to their lower cost. The properties of the substrate to be handled by pumps influence the choice of appropriate pumping technology and pumps (type of material, particle size, DM content, and level of preparation). Pumps should have stop-valves provided for convenient emptying and feeding of digesters and pipes. In many cases, one or two pumps in a pumping station handle the whole feedstock that transit within the biogas plant.

2.1.1.6 Solid feedstock feeding equipment

The solid substrate feeding system consists of transport equipment (such as tractors and loaders) and a conveying system that feeds substrates from bunker silos to containers. Screw conveyors can transport materials in any direction. Crushed coarse substrate should be inserted into the screw windings for maximum performance. Screw conveyors are widely utilized in three main ways: wash-in shaft, feed pistons, and feed conveyor screws. Large amounts of substrate can be delivered directly to the digester at any moment using wash-in shafts. Hydraulic cylinders feed the substrate directly into the digester through feed pistons. It forces the substrate through a hole in the digester's wall. This system is used to reduce the possibility of forming a floating layer. For crushing long fiber materials like air-dried silage, this system has counter rotating mixing rollers. The substrate is fed under the level of the liquid in the digester using a feed screw conveyor. The advantage of this technology is that it prevents gas leakage during the feeding process. Mixing and crushing instruments are sometimes included in this system.

2.1.1.7 Digester Heating System

Maintaining a steady temperature in the AD process is one of the most crucial parameters for high biogas production. Temperature fluctuations must be kept to a minimum since they cause microbial imbalance in the AD process and, in the worst-case situation, process failure. To achieve and maintain a constant temperature for the AD process and to compensate for heat losses, digesters must be heated by external heating sources and isolated. The substrate might be heated during the feeding process (pre-heating) or by a heating system inside the digester. The advantage of preheating the substrate during feeding is that temperature changes inside the digester are avoided. Both forms of substrate heating are used in many biogas facilities.

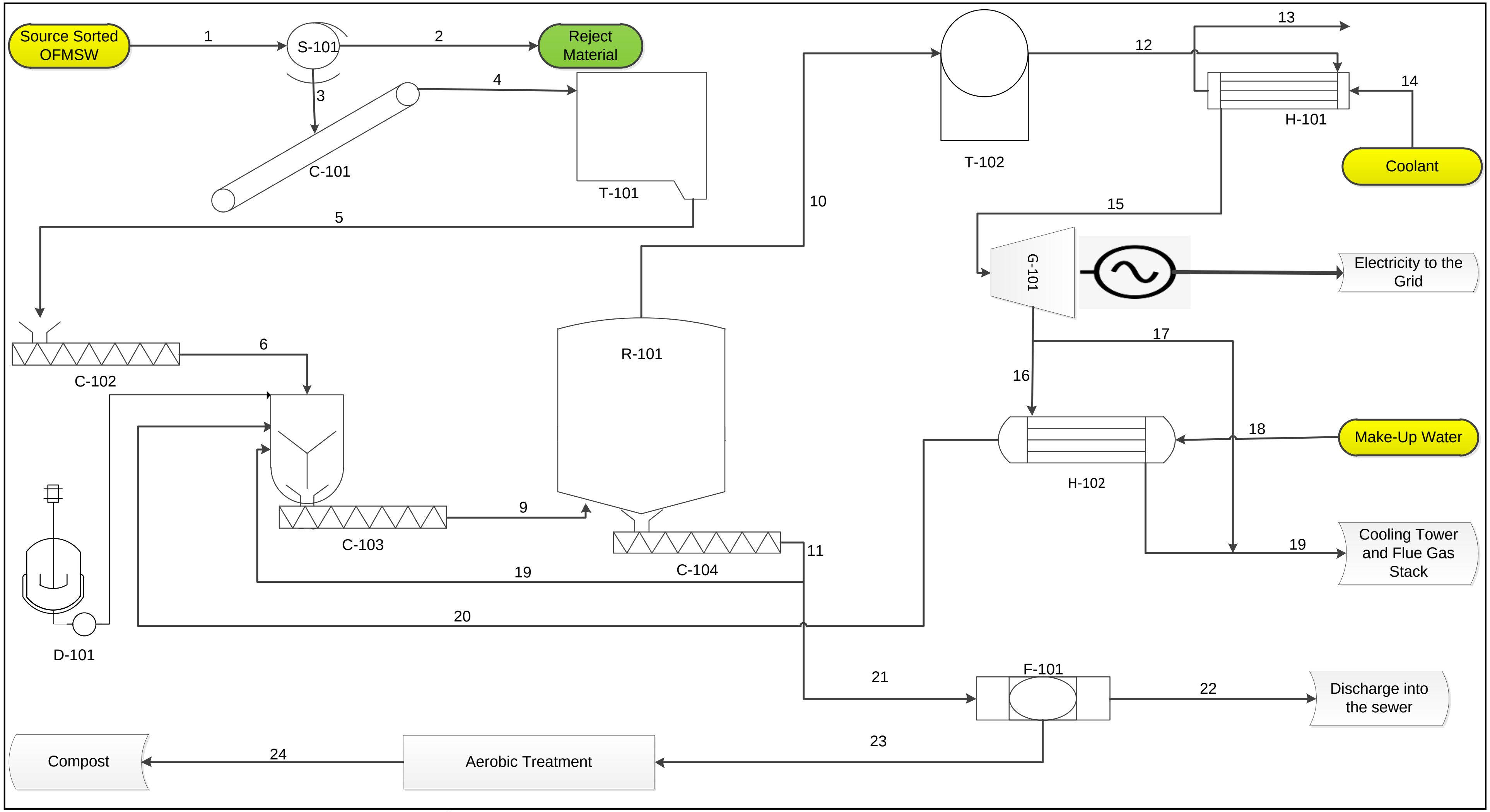


Figure 1: Process flow diagram of the proposed 100TPD OFMSW Anaerobic Digestion Plant

2.1.1 Schematics

The plant design drawings of the 100TPD AD plant are shown in the figures below.

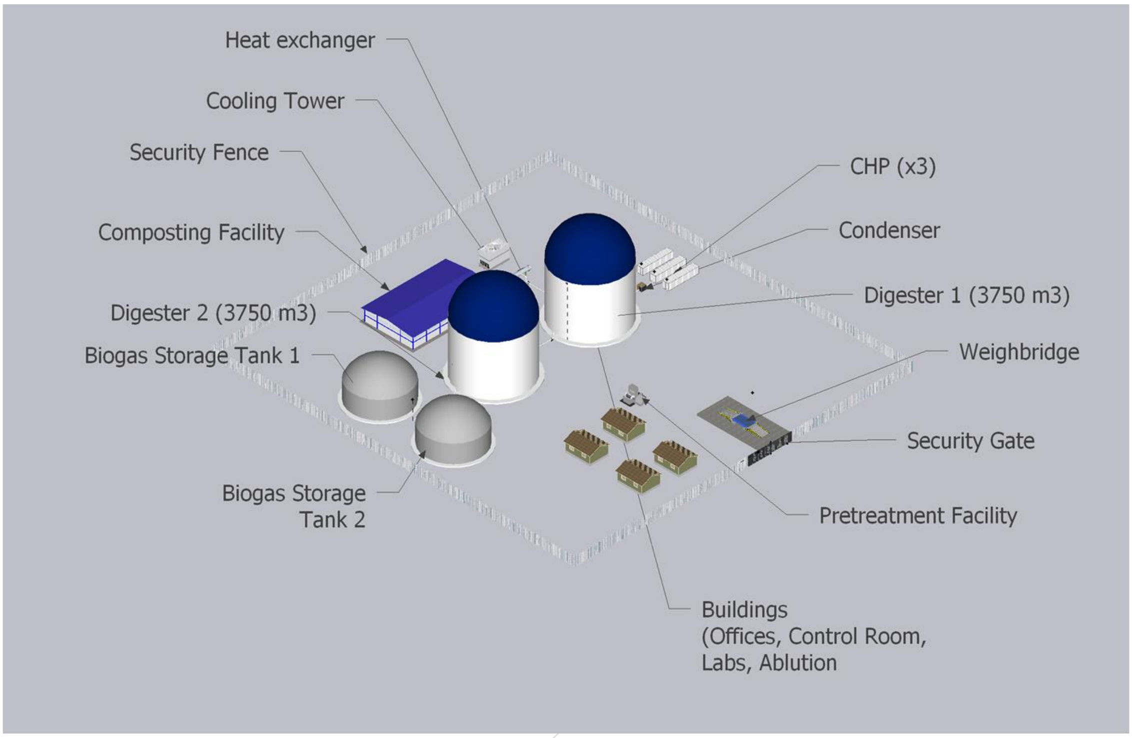


Figure 2: Isometric projection of the plant schematics.

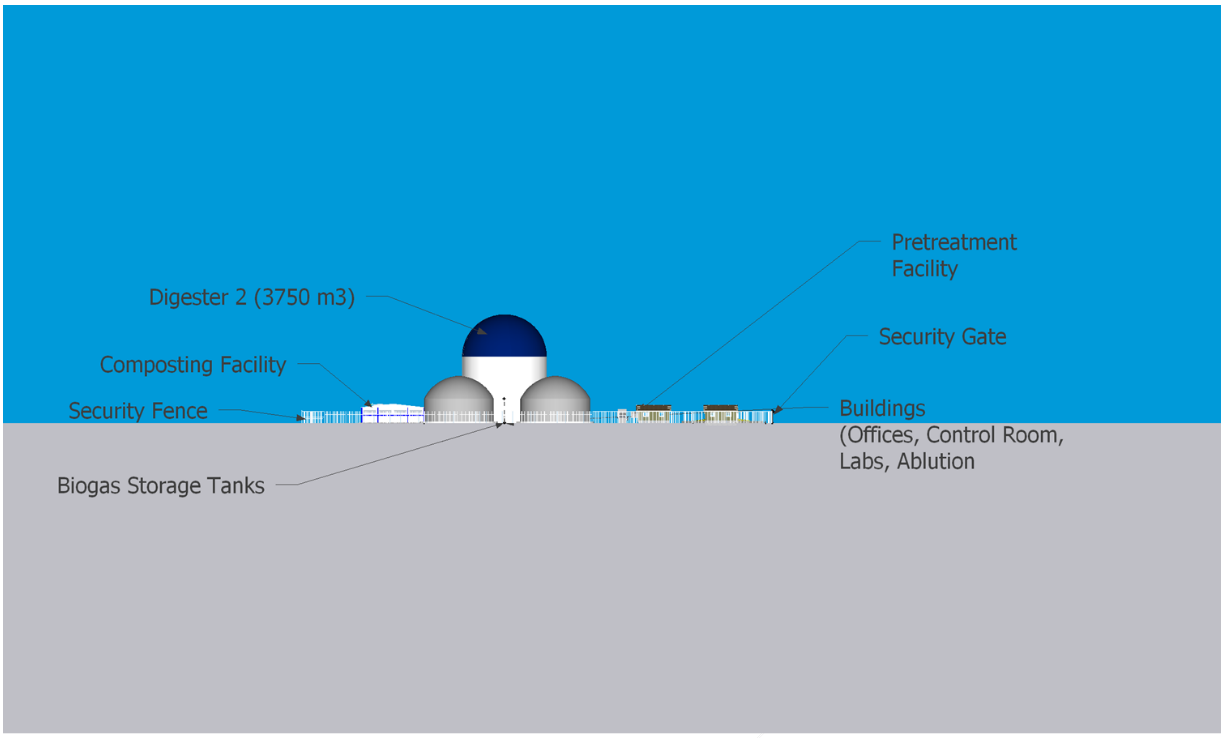


Figure 3: Plan view of the plant schematics(side-view).

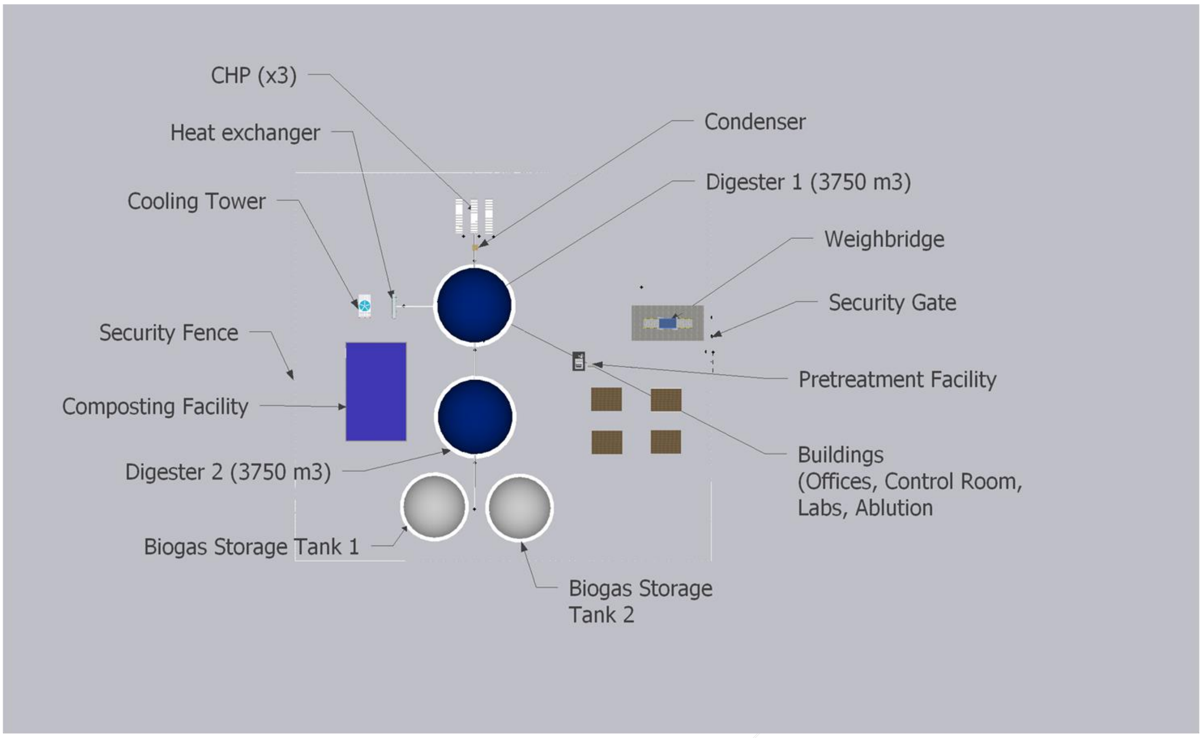


Figure 4: Plan view showing hidden details of plant and description of units (top-view).

2.2 Mass balance and Energy Balance

2.2.1 General mass balance

The designed biogas plant was thoroughly characterized in terms of TS, VS, and a percentage of OFMSW was performed. Appendix A shows the material flow and detailed mass balance of the designed biogas plant. The biogas plant is designed to treat around 100 tons/day of OFMSW (45.63% TS and 90.91% VS). The measured masses were validated by means of a linear equation system, which was based on the law of conservation of mass (equation 1):

$$M = S + E + B \qquad (1)$$

M denotes fresh mass of OFMSW, S mass of solid fraction of digestion residue, E mass of effluent and B mass of the biogas. All masses, expect of biogas were recorded in tons/day. In respect of TS and VS, the following equations are valid:

$$M.TS_M = S.TS_s + E.TS_E + B - W \quad (2)$$

$$M.VS_M = S.VS_s + E.VS_E \quad (3)$$

The biogas plant has one stream of rejected materials identified as pre-treatment reject materials (45.63% TS and 90.91% VS). Large wastes will be manually pre-selected into three categories i.e organic waste, recyclables and residual wastes at the household, market and hotels before disposing the initial mixture to the pre-treatment step and they will be sent to recycling facility or sorting unit and La Laura transfer station. The organic waste will be sent straight to the biogas plant.

During the anaerobic digestion step, 667.3.1 kg of OFMSW will be digested (95 kg of the initial mixture OFMSW and 570 kg and 2.3 kg of recycle streams) and 32343 Nm^3 of the biogas will be achieved. The digestate obtained will not be combined with any bulking agent and will be transferred directly to the composting facility for a period of 2 to 3 weeks. Before being stocked and marketed, the finished compost (TS of 55.30% and VS 50.61%) should be treated with a trommel screen (10 mm cut-off) to remove the residual bulking agent and residual contaminants.

2.2.1.1 Physical pre-treatment mass balance

The OFMSW will be transported to the biogas plant straight from households, market and hotels after being sorted and it must be processed every day. It is anticipated that the heavy/small fraction will be mainly constituted by the organic matter and the pre-treatment process will be continued until the anaerobic digestion stage whereas only 5%will be the reject materials of the pre-treatment step. The specific distribution of the OFMSW in the pre-treatment step was: 5% of the initial OFMSW was rejected in the pre-treatment step (5 tons/day of OFMSW; 43.63% of TS, 90.91%) and 95% of the OFMSW moved to the pre-treated OFMSW storage tank then grinder/pump system and the anaerobic digestion step.

2.2.1.2 Anaerobic digestion stage

The pretreated material will pumped into form the storage tank, mixed with six parts of the digested solids as an innoculum and low-pressure steam for raising the temperature to 50ºC in an integrated mixer-screw pump. The mixture will then be pumped into the reactor, where the organic matter will anaerobically digested to produce biogas. As already indicated above, given that the FW and YW handled at selected site (La Laura Transfer Station) is not suffient for to provide 100TPD of feedstock to the plant, the waste will be supplemented with the OFMSW handled at the Mare Chicose Landfill. As such, biogas yields will have to be re-calculated for mixture of the two OFMSW.

The total FW handled at the two sites (La Laura transfer station and Mare Chicose Landfill) is 15 333 tons annually, this is when an 85% collection efficiency of the waste is considered, this mean that the is a shortfall of 14667 TPY of organic waste to meet 30000TPY required by the plant. This shortfall will be met by supplementing the waste with YW handled at the two site. Thus, the ratio of the FW:YW will be 1:1.05. The ratio is assumed that it will constant throughout the year, this is done to simplify the calculations, as there is no data on the variation of ratio on a daily basis. The calculations were done as explained in deliverable 3, taking into account the limiting factors and the results are shown in Table 1.

Table 1: Methane Yield of Subtrate for AD Plant

Substrate	TBMP (Nm^3 CH_4/tonne VS)	BMP (Nm^3 CH_4/tonne VS)	FSMY (Nm^3 CH_4/tonne VS)
FY	414.9	218.4	185.6
YW	384.6	202.4	172.0
OFMSW **(FW:YW 1:1.05)**	400.1	210.6	179.0

Biogas Production

Dry Biogas

Using the methane yield determined above, its volumetric flowrate in the biogas can be determined using equation 4. The mass balance will be done on volatile solid basis, thus, the full-scale methane yield (FMSY) to be used in equation 4, is per volatile solids than per wet waste.

$$Q_{methane}\ (m^3/day) = FSMY \cdot m_{OFSMS\ in} \tag{4}$$

The biochemical conversion of OFMSW to biogas can be represented by Boyles (5), thus, the molar fraction of methane and carbon dioxide can be computed using equation 6 and 7, respectively, assuming that the dry biogas is only composed of these two components.

$$C_aH_bO_cN_d + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{d}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8}\right) CO_2 + dNH_3 \tag{5}$$

$$x_{CH4\ dry\ biogas} = \frac{4a+b-2c-3d}{8a} \tag{6}$$

$$x_{C02} = \frac{4a-b+2c+3d}{8a} \tag{7}$$

The flowrate of dry biogas produced from OFMSW can then be determined using equation 8.

$$Q_{dry\ biogas}(m^3/day) = \frac{Q_{methane}}{x_{CH4}} \tag{8}$$

$$\rho_{dry\ biogas}\ (kg/m^3) = \frac{x_{CH4}M_{CH4}+x_{CO2}M_{CO2}}{22.4} \tag{9}$$

$$m_{dry\ biogas} = Q_{dry\ biogas} \cdot \rho_{dry\ biogas} \tag{10}$$

Moisture content of biogas

The biogas produced in the digester will leave the reactor saturated with water vapor. The moisture content of the biogas can be computed using equation 11 (Laizāns & Vardanjan, 2017). Therefore, equation can be used to work out the water vapor flowrate in biogas stream.

$$c_{MC\ biogas}(kg\ H_2O/kg\ dry\ biogas)\ = \frac{1}{1000}(7.59134X10^{-6}T^4 - 2.85632X10^{-5}T^3 + 0.010746T^2 + 0.329286T + 3.82995) \tag{11}$$

$$m_{H2O\ gas} = c_{MC\ biogas}\, m_{dry\ biogas} \tag{12}$$

The biogas flowrate in the biogas stream will be the sum of the mass flowrate of the biogas and the flowrate of water vapour.

$$m_{biogas} = \ m_{dry\ biogas} + m_{H2O\ gas} \tag{13}$$

Saturated biogas

The presence of moisture in the biogas stream will change the molar composition of the stream. The molecular weight of dry biogas can then be determined using equation 14:

$$M_{dry\ biogas} = x_{CH4}M_{CH4} + x_{CO2}M_{CO2} \tag{14}$$

The determined molar mass of the dry biogas can thus be used to determine the molar flowrate of the biogas in the biogas stream.

$$n_{dry\ biogas} = \frac{m_{dry\ biogas}}{M_{dry\ biogas}} \tag{15}$$

Thus, the molar composition of the stream can then be determined using the following equation:

$$x_{CH4\ biogas} = \frac{x_{CH4} n_{CH4}}{n_{dry\ biogas} + n_{H2O}} \tag{16}$$

$$x_{CO2\ biogas} = \frac{x_{CO2} n_{CO2}}{n_{dry\ biogas} + n_{H2O}} \tag{17}$$

$$x_{H2O\ biogas} = \frac{n_{H2O}}{n_{dry\ biogas} + n_{H2O}} \tag{18}$$

The density of the saturated biogas can thus be calculated using equation 19, and subsequently, the calculation of saturated biogas volumetric flowrate in the

$$\rho_{biogas}\ (kg/m^3) = \frac{x_{CH4} M_{CH4} + x_{CO2} M_{CO2} + x_{H2O\ biogas}}{22.4} \tag{19}$$

$$Q_{biogas} = \frac{m_{biogas}}{\rho_{biogas}} \tag{20}$$

Solid Balance

Fixed Solid

The TS of the feedstock is composed of fixed solids (FS) and VS. The FS are inorganic materials that are not biodegradable. The FS mass balance is given by equation 21.

$$\frac{dFS}{dt} = FS_{in} - FS_{out} + FS_{produced} - FS_{reacted} \tag{21}$$

Because FS are not biodegrable, thus no FS solid will be consumed or produced in the reactor, under steady state, the FS flow into the digester will be similar to that leaving the reactor.

$$FS_{out} = FS_{in} \tag{22}$$

Volatile Solids

The VS undergoing biochemical reaction produces biogas and biomass. The balance of VS around the digester can be represented by equation 23.

$$\frac{dVS}{dt} = VS_{in} - VS_{out} - VS_{consumed} \tag{23}$$

The biomass produced in the digester will leave the digester in the digestate stream and the fraction of VS mass will leave the digester as biogas. The net VS consumed in the digester will be the mass of the dry biogas leaving the reactor. Therefore, under steady state conditions, the VS content of the digestate can be calculated using equation.

$$VS_{consumed} = m_{\ dry\ biogas} \tag{24}$$

Thus, the volatile solids in the digestate can be worked out from equation 25.

$$VS_{out\ reactor} = VS_{in\ reactor} - m_{dry\ biogas} \tag{25}$$

Total solids

The total solid content of the digestate, will be the sum of the VS and FS of the digestate.

$$TS_{out} = VS_{out} + FS_{out} \tag{26}$$

Water balance

In the reactor, water will be required to convert organic matter to biogas as shown in equation 5. The water content of the digestate leaving the reactor can be determined in two ways:

- Determine quantity of water that has been consumed in the reactor during metabolism of the organic matter and that is leaving the digester in the biogas stream.
- Using the TS content of the digestate, determine the moisture content of the digestate and workout the mass flowrate of the water leaving the digestate.

The second approach will be taken in determining the mass flow rate of water in the digestate. The overall mass balance around the reactor can be given by:

$$m_{feed} = m_{biogas} + m_{digestate} \tag{27}$$

Therefore:

$$m_{water\ digestate} = \left(1 - \frac{TS_{out}}{m_{digestate}}\right) m_{digestate} \tag{28}$$

2.2.1.3 Composting process stage

Composting is a cost-effective alternative to transporting organic waste to a landfill because it may be done on-site. Fertilizer and heat are produced as a result of the process. Carbon dioxide, a greenhouse gas, is also created and released into the environment. There is a considerable risk of impurities, such as glass, in compostable waste, rendering the finished product worthless. Figure 5 shows a schematic representation of the compost facility as well as the overall mass balance in the most essential operations of the composting process. The decomposition phase takes place in a closed composting reactors with controlled aeration, watering, and gas collection and treatment using a wet scrubber and a biofilter for two weeks, while the curing phase takes place in forced-aerated windrows open to the atmosphere for 6 to 8 weeks without gas collection. The 18.3tons of OFMSW and 1.77 tons of pruning waste will be processed at the compost site. In the decomposition phase, 17.50 tons of OFMSW were estimated. While the composting procedure (tunnel and curing phase) was predicted to be 15.17 tons, this did not include the final compost refining step. The composted material will be filtered in a trommel with a 10 mm mesh during the post-treatment process. This stage separates compost from the non-degraded bulking agent (which can be reused) as well as the thin inorganic particles and plastic that remain (refuse). Compost, pruning waste, and garbage were calculated to weigh 12.9, 1.77, and 0.5 tons, respectively.

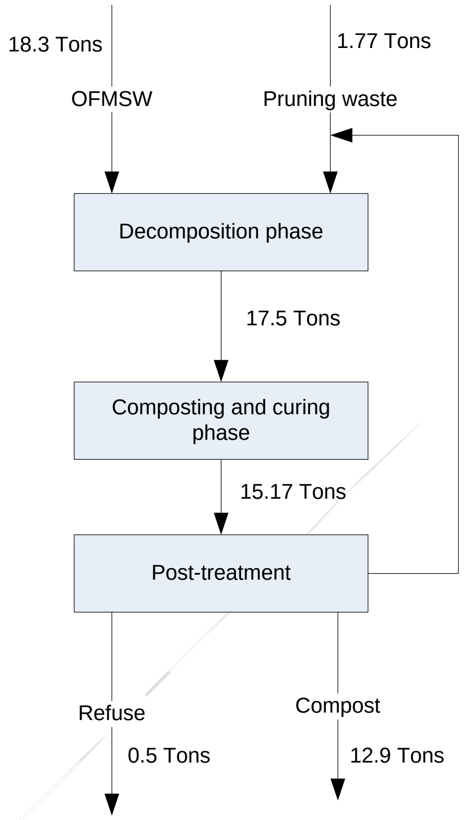


Figure 5: Schematic diagram of the composting facility composting mass balance (18.3 tons of OFMSW input is selected as base for mass balance).

2.2.1.4 Summary of Mass Balance

100 TPD of ss-OFMSW will be received and it will then be sent to the rotary screen to remove impurities. 5 TPD of waste will be rejected and 95 TPD will be recovered as pretreated waste. The pretreated waste will mixed with 2.3 TPD of low-pressure steam and digested in an AD reactor where 32343 Nm^3/day of saturated biogas will be produced. The saturated biogas will sent to the chilling

unit for moisture removal, where the volume will be reduced to 27387 Nm^3/day of dryed biogas. The composition at this point will be methane and biogas, with less than 1% of moisture. The biogas will sent to biogas turbine for electricity generation, the waste gas will be sent to the heat exchanger for generation of 2.3 TPD of low pressure steam. The digestate will be sent to filter press, where 39.6 TPD of filtrate will be recovered.

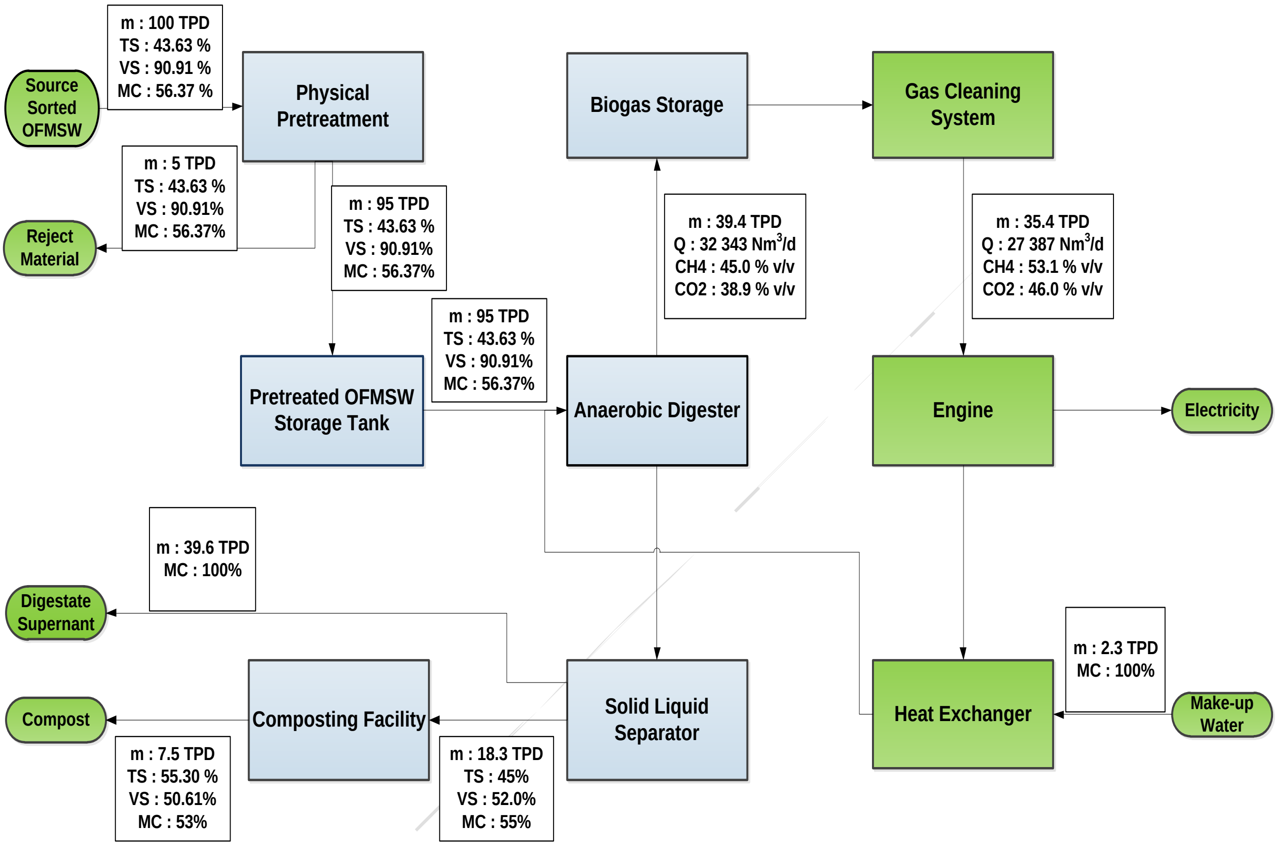


Figure 6: Summary of mass balance of the 100TPD AD for source-sorted OFMSW.

2.2.2 Energy balance

The energy input demand Q_I is determined by the temperature and mass of the input material, the environmental daily mean temperature, wind speed, and the amount of heat energy used to heat the input material. It can be approximated using the following equation:

$$Q_I = Q_H + Q_R + Q_E \tag{29}$$

Where Q_H is the energy required to heat the input material to AD reactor, Q_R the energy to maintain the process temperature of the reactor and Q_E the electric power to run the electric motors for mass transfer equipment. The energy required to heat the input material up to the process temperature t_i is calculated on the assumption, that the temperature of the input material is the same as the average daily mean temperature t_a. Because the specific heat capacity of the input material is unknown, we assume that it is equal to the specific heat capacity of water:

$$Q_H = (M + E).1.17\ Whkg^{-1}K^{-1}.(t_i - t_a) \qquad (30)$$

The energy required to heat the reactor Q_R is equal to the conductive-convective heat transfer from the reactor surface to the surrounding environment, which can be approximated using the following equations:

$$Q_R = k.A.(t_i - t_a).24\ h\ d^{-1} \qquad (31)$$

where A names the reactor surface and k the k-value, which is calculated by equation 32

$$K = \frac{1}{\left(\frac{1}{\alpha_{\frac{substrate}{steel}}} + \frac{d_{steel}}{\beta_{steel}} + \frac{d_{air}}{\beta_{air}} + \frac{1}{\alpha_{\frac{metal}{air}}}\right)} \qquad (32)$$

The heat transfer coefficient α and the thermal conductivity coefficient β of the reactor wall elements are compiled in Table 2.

Table 2: Parameters for calculations of the conductive-convective heat transfer of the reactor surface.

Parameter	Unit	Value	Reference
$\alpha_{substrate/steel}$	$Wm^{-2}\ K^{-1}$	382	Schäfer et al., 2006
d_{steel}	m	0.01	Schäfer et al., 2006
β_{steel}	$Wm^{-1}\ K^{-1}$	40	Brockmann, 1987
d_{air}	m	0.02	Schäfer et al., 2006
β_{air}	$Wm^{-1}\ K^{-1}$	0.024	Brockmann, 1987

* β thermal conductivity, t Temperature, α heat transfer coefficient, d wall thickness.

A separate meter will track the entire plant's electric power consumption. We calculate the heat losses in the burner's exhaust gases using the measured gas consumption of the gas burner GB and the calculated energy input for process heating:

$$Q_{EX} = G_B . c . 10^4 Whm^{-3} - Q_M - Q_R \tag{33}$$

Where c is the average volume percentage of carbon dioxide in the biogas, which is derived from the biogas yield AD reactor:

$$c = (G_1 . c) . (G_1)^{-1} \tag{34}$$

2.3 Schematic Design of AD Plant Units

2.3.1 Pre-treatment Unit

Pretreatment is a process that involves a mix of physical and chemical adjustments to anaerobic digestion substrates to make them suitable for higher biogas output. Mechanical pre-treatment is a straightforward method of enhancing biomass specific surface area and availability. Particle size reduction increases biogas yield while also lowering digester viscosity and reducing the creation of floating layers, which cause difficulties in biogas reactors by blocking outlets, making food unavailable for digestion, and interfering with gas escape. Feedstock sorting and removal of undesired materials, as well as crushing and mashing, will make up the physical pre-treatment unit. In storage tanks, pollutants will be separated by sedimentation and periodically removed from the bottom of the tanks.

2.3.2 Storage Tank

A bunker silo will be used as a substrate storage facility. Substrate can be stored in a bunker silo for 6 months to a year. Delivery intervals, quantities to be stored, and daily amounts fed into the digester all influence the size of the storage facilities. The dimensioning of the storage facilities is determined by delivery intervals, the quantities to be stored and the daily amounts fed into the digester. The designer should take into consideration that a part of the tank (about 10%) is empty to prevent the manure/liquid to reach the top rim of the tank. As a result, these tanks should be built to handle a variety of design loads, including the loads of soil outside the digester that is buried underground and the loads of liquid held inside the digester. Large cylindrical concrete tanks, some of which are partially underground, are commonly used to hold liquid manure. According to Ghafoori & Flynn, 2007, these tanks range in size from 18 to 33 meters in diameter, with heights ranging from 2.4 to 4.9 meters and a uniform wall thickness of 150 to 200 millimeters.

Figure 7: Bunker silo made of concrete

2.3.3 Reactor

2.3.3.1 Reactor Technologies

The anaerobic digester is the unit in which organic matter are degraded to the energy-rich biogas under the absence of oxygen. The design of the unit should ensure that conditions are optimised to allow for maximum biogas production from the fed feedstock. In deliverable 4, a single stage high solids(SSHS) reactor was selected as the preferred technology for biogas production from the OFMSW for the proposed plant.

Several reactor technologies have been commercialized for dry anaerobic digestion whereas highlighted in output 4, and in this work, the technologies will further be explored. Three dry technologies were identified as possible candidates for a future AD facility based on early screening. = The three most popular technologies as SSHS are Kompogas, Valorga and Dranco process.

Kompogas is a thermophilic process that takes place between (55 and 60℃). A plug flow digester with a retention time of 15-20 days is used in the Kompogas technology. The impellers slowly mix the material as it flows through the reactor for homogenization and de-gasification of biogas. The garbage is shredded before being sifted for pollutants like plastic and glass. Before the digester, any ferrous metal material is recovered using a magnetic separator. Waste is sent through a second shredder or sieve, then to an intermediate bunker, which serves as a mixing and regulating device for the flow to the digester. The shredded waste is kept in this tank for 2 days, during which time it warms up a little before entering the digester. To modify the feedstock moisture content to 28% dry solids content, water from the dewatering unit is added to the trash in the storage unit. The shredded trash is delivered to the digester, which is usually a concrete or steel tank, by a piston pump. A heat exchanger heats the waste from 25oC to 55℃. While in the storage unit, the waste matter heats up as well.

Kompogas

Kompogas anaerobic technology is licensed under the Hitachi Zosen Inova (HZI) based in Switzerland. The company designs, builds and operate biogas plants based on this technology (HZ-Inova, 2021). The technology employs a horizontal plug flow reactor with the mixing rotors mounted inside. The coming feedstock is mixed with the digestate for inoculation and it is then pumped into the reactor, this to avoid acid-buildup on the front end of the reactor and to keep heavy particles suspended (Rapport et al, 2008 & Elsharkawy et al, 2019). The implellers slowly mix the material as it flows through the reactor for homogenization and de-gasification of biogas from the reactor contents (Elsharkawy et al, 2019). This technology is suitable for feedstock that has a solid content of between 23 – 28 % (La Pera et al, 2020). The technology has biogas yields which ranges from 80 – 160 m^3/ tonne of feestock at hydraulic retention times of between 15 and 29 days (La Pera et al, 2020 & Elsharkawy et al, 2019). The technology needs careful control of the solid content feedstock, and for higher solids content, the feedstock can be diluted using fresh or supernatant filtered from the digestate paste. For solid content below the range, heavy particles will settle in the reactor and for content that is higher, the reactor content may not flow (Elsharkawy et al, 2019). Digesting is a one-step, semi-continuous, high-solids process. The reactors are vertical cylinders that do not have any mechanical equipment. This enables the process to run in high-solids environments without causing circulation or other problems. Biogas is injected at high pressure into the reactor's bottom every 15 minutes to mix the contents. The gas injection ports become clogged with time, making maintenance difficult. The Valorga method dilutes and pulps the organic fraction to a solids concentration of around 30%. Conveyor belts, screws, and powerful pumps built specifically for highly viscous materials are used to transport and handle the material. Because this sort of equipment is so durable, the only pre-treatment required is the elimination of coarse contaminants larger than 1.73 inches (40 mm). At a mesophilic temperature of 35 - 40ºC, retention period in the Valorga plant is 18 - 25 days. The plant feedstock has an average dry matter concentration of 25% to 30%.

DRANCO is a single-stage, dry, thermophilic anaerobic fermentation method with a short aerobic curing step. During the AD phase, the organic material is converted to biogas in an enclosed vertical digester that can handle a wide range of incoming materials with solids or dry matter contents ranging from 15% to 40%. Before entering the digester, steam is fed into the waste stream to raise the temperature to 50°C. The steam adds moisture to the entering feedstream, and DRANCO has discovered that steam has a high heat transfer efficiency. The method requires very little water and is quite adaptable in terms of feedstock needs. Thermophilic temperatures of 50 - 55°C are ideal for digestion. Once a day, the top of the digester is fed with incoming feed material. The materials retrieved at the bottom of the digester are re-circulated, mixed with fresh wastes and pumped to the top of the digester, where they are mixed. The biogas yield is between 80-120 m^3/t of waste feedstock and the reactor retention time is between 20 and 30 days. Before being transported to gas engines or combined heat and power (CHP) facilities, the collected biogas is sometimes briefly kept for additional purification. The digested material is removed from the digester's bottom. It is subsequently dewatered to a total solids (TS) level of about 50% and aerobically stabilized for about two weeks. Soil blenders, landscapers, and customers can purchase the solid composted product, which is used as a soil conditioner. Although the completed compost contains plant nutrients (nitrogen, phosphorous, and potassium), its primary benefit is as a soil conditioner rather than a fertilizer.

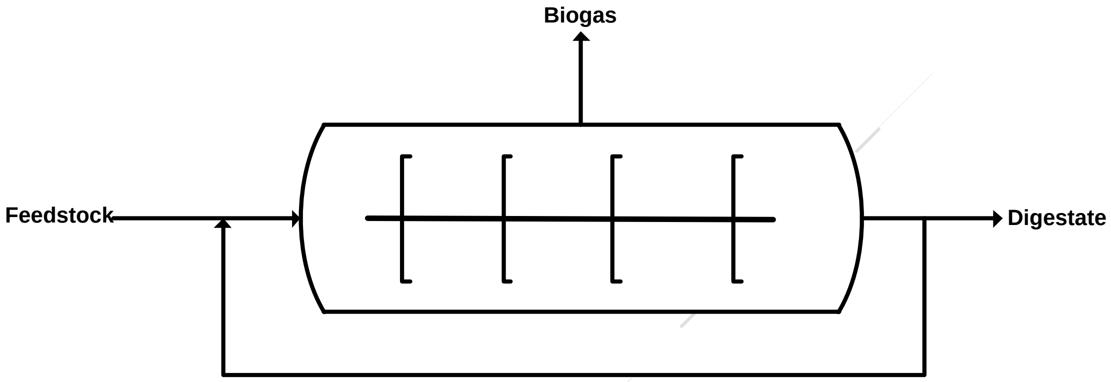


Figure 8: Schematic diagram of the Kompogas reactor technology for dry anaerobic digestion

Valorga

Valorga anaerobic digestion reactor developed in France (Valorga Internation, 2006). The technology employs a vertical reactor with inner perforated wall that is located at about 2/3 of the diameter of the reactor tank for horizontal plug flow. The produced biogas is compressed and portion of it is bubbled into the reactor for homogenization of reactor contents. The feedstock to the reactor must have solid content of between 25 and 35%. The reactor is operated at mesophilic temperature regimes and retention times of 18 to 23 days, yielding 80 – 180 biogas per tonne of wet waste.

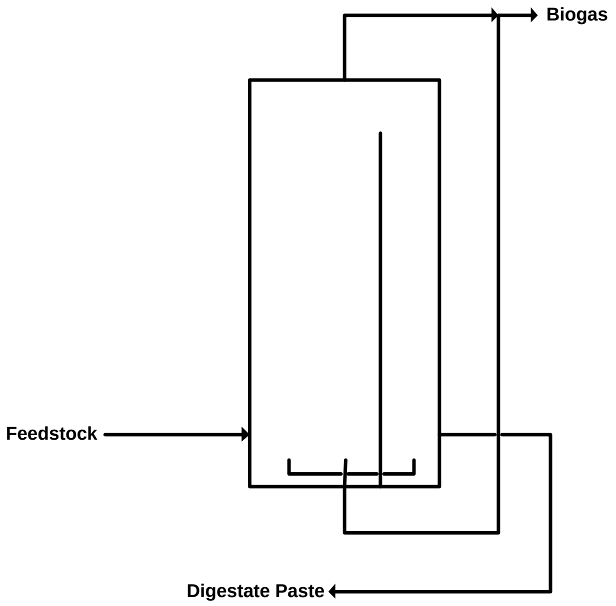


Figure 9: Schematic diagram of Valorga Anerobic Digestion technlogies

Dranco

Dranco anaerobic digestion technogy was developed in Belgium. The technology consist of vertical reactor which consist of internal feed pipes that feed the feedstock at the top of the reactor, such that it operates as vertical plug-flow. The reactor can handle feedstock with the TS content of 20 - 50%. The technology can be operated in both mesophilic and thermophilic temperature regime, with operating temperature ranging between 50 and 55 ^oC (De Baere, 2010). The digester does not have any heating pipes, the temperature of digester is maintained by mixing the digester feed with steam. The process can handle organic loading rate of up to 15 kg VS/m^3 day, however, typical designs are about 12 kg VS/m^3 day, yielding about 100 – 200 m^3 of biogas per tonne of wet waste (Rapport et, 2008). The digester is agitated through the re-circulation of the digestate.

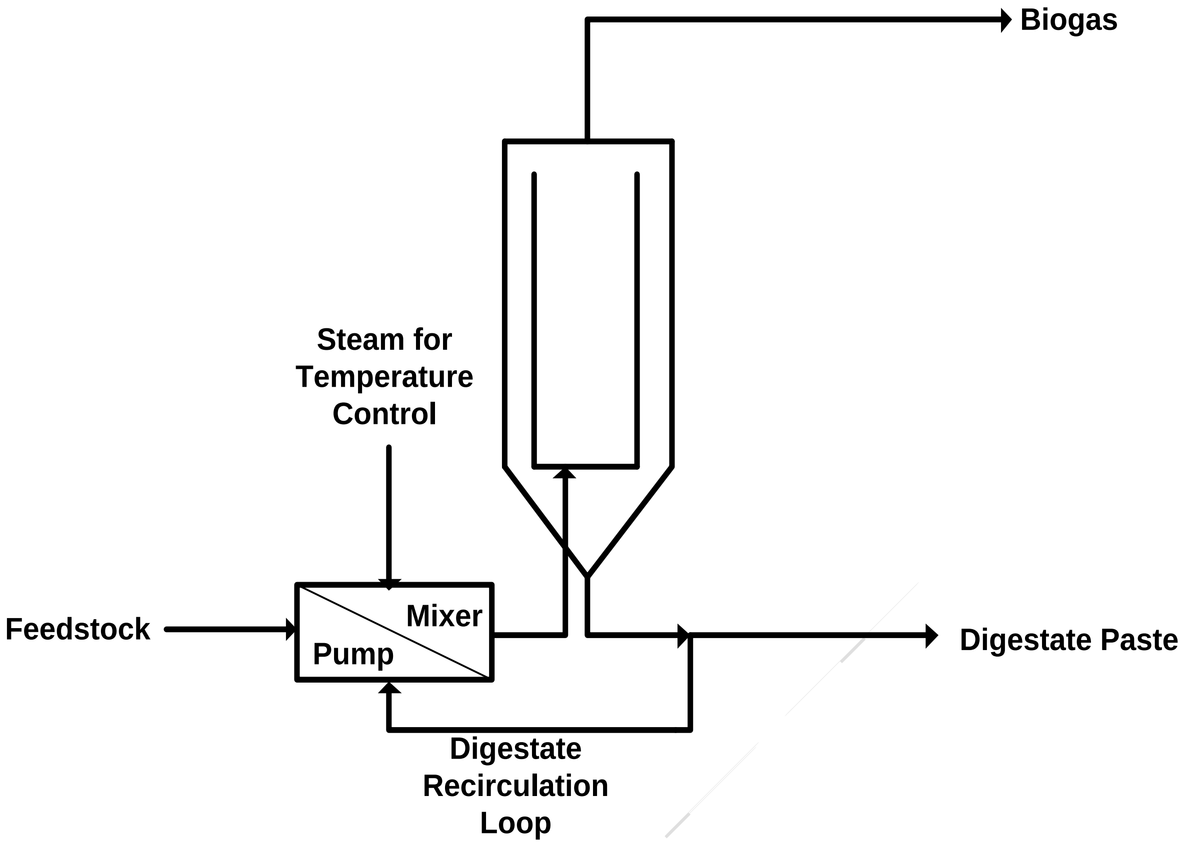


Figure 10: Schematic diagram of Dranco process for anaerobic digestion of OFMSW

Table 3: Single Stage Dry Anaerobic Digestion Reactor Technologies

Technology	Temperature	Solid Content (%)	Biogas Yield (m^3/tonnes of input material)	Country	Citation
Kompogas	Thermophillic	23 – 28	80 – 160	Switzerland	La Pera et al, 2020 Elsharkawy et al, 2019 Raport et al, 2020
Valorga	Mesophillic	25 – 35	80 – 180	France	Valorga International, 2006 Le Pera, 2021 Maleki-Ghelichi & Sharifi, 2017.
Dranco	Mesophillic	30 – 40	100 - 200	Belgium	De Baere, 2010 Le Pera, 2021 Maleki-Ghelichi & Sharifi, 2017.

2.3.3.2 Reactor Sizing

Given the wide application of Dranco process and the solid content of waste that is to be received at the proposed AD plant, Dranco technology will be more suitable for plant. Thus the design of the reactor in this work will be based on this technology. As already indicated above, the technology can process OLR up to 15 kg VS/(m^3 d). However, in this case the digester will be designed for a modest OLR of 12 kg VS/m^3 day. The working volume of the digester that needs to installed can be calculated from the equation :

$$V_{working\ volume} = \frac{VS_{in\ reactor}}{OLR} \qquad (39)$$

Where $V_{working\ volume}$ is the volume of the reactor (m^3)

$VS_{in\ reactor}$ is the mass flowrate of VS the (kg/day)

The total volume of the reactor will be the working volume and 10% of working volume will be the headspace of the reactor. The design information of the anaerobic digester is shown in Table 4.

Table 4: Anaerobic digester design for the proposed 100 TPD AD plant

Organic loading Rate	12	kg VS/m3 day
Temperature	55	oC
Working Volume	6776	m3
Headspace	678	m3
Total Volume of Digester	7500	m3
Number of Reactors	2	Digesters
Reactor Volume	3750	m^3
Reactor Height	21	m
Reactor Diameter	15	m

Given that the large volume of digestion volume of is required to maintain the organic loading rate at 12 kg VS/m3 day, this will require the capacity to be split into two. It might not be practical to build very high or very tall structures. Two digesters that will be run in parallel. The diameters of the reactor (15 meters) was taken to be similar to that in the work of De Baere(2010) and the ratio of reactor volume to height (3150 m^3:25 m) was also assumed to be similar.

2.3.4 Biogas Storage Tank

Biogas production rates from the anaerobic digesters are often not constant, and as such, storage tanks must be in place to dampen the fluctiuations in gas production and ensure that constant fuel is been sent to cogeneration plant. In the Output No. 4, different biogas storage systems were described in details. In this work, low pressure biogas system will be considered given the lower capital, operation and maintance costs compared to medium and high-pressure biogas storage system.

Various researchers have reported different storage times for biogas. Golsh and Helm (2006) reported 4 hours, Elder and Schaltz(2006) reported 5-12 hours and Dublein and Steinhauser (2011) reported 12 – 18 hours. Most of biogas plants are reported to store produced biogas for 2-3 hours. As such, the biogas in this for the proposed plant should be stored for 2.5 hours, to minimize the capital cost of biogas storage. Given 1348 m3/hour of biogas will be produced, 3400 m^3 of biogas storage tank capacity will be required. Low biogas storage tank have a capacity of up to 2000 m^3. As such, 2 storage tanks will be required with one having volume of 2000 m^3 and the other with the holding capacity of 1400 m^3.The design information for the biogas storage is summarized in table 5.

Table 5: Blogas Storage Tank Design

Storage Time	**2.5**	**hours**
Biogas Flowrate	1348	m3/hour
Storage Tank Capacity Required	3400	m3
Number of storage tanks	2	Tanks
Storage tank 1	2000	m^3
Tank 1 Shape	Spherical	
Diameter	19.7	m
Hieght	19.7	m
Storage tank 2 volume	1400	m^3
Shape	Spherical	
DIameter	17.5	m
Height	17.5	m

2.3.5 Chiller for Biogas Moisture Removal

As indicated above, the biogas that will be leaving the reactor, will be saturated with water vapour, and this must be removed from the reactor prior to combustion to prevent lowering the heat content of the biogas and any presence of hydrogen sulphide will react to form sulphuric acid that will corrode material of engine internals. This moisture can be removed using various techniques which include compression, absorption to hygroscopic materials and use of filters. Cooling the biogas to 5^oC is the cheaper and the most commonly used method for moisture content. As such, this method will be used to in this study. To determine how much moisture will be removed from the biogas, the moisture content of the biogas feed to the chiller and the biogas leaving the system will be determined using equation 9. The water vapor removed from the biogas will be the difference of the two biogas streams. The heat capacities of the three components of biogas can be given by the following equations (Vardanjans et al, 2015):

$$C_{p\,CH4} = 0.628326\frac{Tk}{T} + 0.752532 + 0.582779\left(\frac{T}{T_k}\right) + 0.082044\left(\frac{T}{T_k}\right)^2 - 0.010773\left(\frac{T}{T_k}\right)^3 \qquad (36)$$

$$C_{p\,H2O} = \frac{143.05 - 183.56\cdot\theta^{0.25} + 82.751\cdot\theta^{0.5} - 3.6989\cdot\theta}{18} \qquad (37)$$

$$C_{p\,CO2} = \frac{-3.7357 + 30.529 \cdot \theta^{0.5} - 4.1034 \cdot \theta + 0.024198 \cdot \theta^2}{44} \tag{38}$$

Where $\theta = \frac{T}{100}$

The energy that needs to be absorbed by the coolant, can be calculated using equation .

$$Q = m_{biogas} \int_{T_1}^{T_2} C_{p\,biogas}\, dT + m_{water\ vapour\ removed} * \Delta Hevaporation \tag{39}$$

$$C_{p\,biogas} = \overline{x}_{CH4} C_{p\,CH4} + \overline{x}_{CO2} C_{p\,CO2} + \overline{x}_{H2O} C_{p\,H2O} \tag{40}$$

Using the equation above, the heat that needs to be removed from the biogas to reduce the temperature to 5°C was calculated and the power requirement of the unit is shown in Table 6.

Table 6: Moisture removal unit design of the produced biogas

Biogas Flow	25.41245829	TPD
Temperature of Biogas Stream into the chiller	23.3	°C
Temperature of biogas stream leaving the chiller	5	°C
Mass fraction of CH4 biogas entering the chiller	0.2907	-
Mass fraction of CO2 biogas entering the chiller	0.6904	-
Mass fraction of Water	0.024	-
Moisture content of biogas into the chiller	0.01917	t water vapor/t dry biogas
Moisture content of biogas leaving the chiller	0.005746	t water vapor/t dry biogas
Mass flowrate of water removed	0.47	t water/day
Q	22.97	kW

2.3.6 Electricty Generation unit

The dry biogas leaving the chilling unit, will be directed to the electrical generation plant where its contained chemical energy will be released by combustion for conversion into mechanical energy, which will subsequently be converted to electrical energy. The waste gas emanating from the unit has high thermal energy, this energy can be recovered as heat for use on-site. The conversion of chemical to mechanical energy is achieved through the use of prime movers. There are various types of movers that can be employed, and this include gas engines, gas turbines, microturbines and stirling engines. Fuel cells are different to listed movers as it converts the chemical energy via electrochemical reactions directly to electricity.

2.3.6.1 Gas Engines

Gas engines are the most widely applied primer movers for electricity generation from biogas. The capacity ranges from few kilowatts to 10MW, with typical lifespan of 60 000 operating hours. The electrical generation efficiency is typically between 35-40%, with efficiency increasing the with the generation capacity of the unit. Efficiency for small units are around 30% and 40% for large engines.

There are two types of gas engines used as primer movers, four stroke lean-burn engines (Gas-Otto engines) and pilot-injecting engines (modified diesel engines). The lean burn engines employ spark plugs for ignition of the fuel in the engine. These engines are more suitable for small-scale biogas plant as their generating capacity can go up to 100kWe. The engines can be modified for large biogas plants with higher electrical efficiency.

Figure 11: Lean-burn (Gas-Otto) engine for electricity generation from biogas (source: Siemens, 2021)

Pilot-injecting engines use oil for igniting the fuel. The ignition oil can either be fossil fuel diesel, heating oil, biodiesel (a mixture of rapeseed and methyl esters), or vegetable oils. The temperature of exhaust gas from two engines can go up to 120^{o}C, and the thermal energy can be recovered and used for generation of hot water.

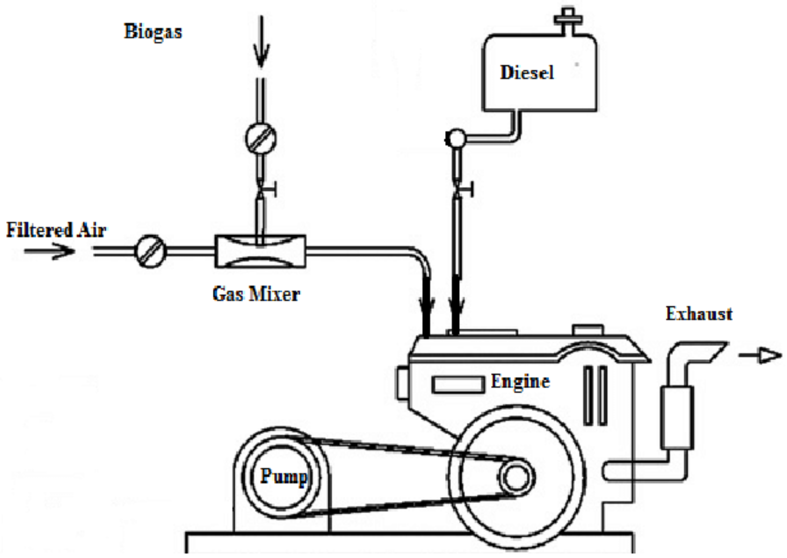


Figure 12: Schematic diagram of pilot-injecting engine for electrcity generation from biogas (source: Khalil, Zhao and Maqsood, 2014)

2.3.6.2 Stirling Engines

Stirling engines are different to gas engines in that there is no internal fuel combustion, the fuel is combusted out and used as heat source for heating the internal gas medium. The gas medium is it is circulated through cooling zone and heat zone; as the temperature decreases, the gas compresses and as the temperature increases it then expands. This cyclic compression and expansion, moves the engine pistons which are connected to an electrical generator by a shaft. The generation capacity of the engines ranges from 1kW to 25kW and the electrical generating efficiency ranging from 24 – 28%. The exhaust gas leaves the engine at temperature of 250 – 300 ^{o}C, with a potential stream for generation of hot water/steam. The engine has low maintance cost but it has high investment cost with limited commercial applications, as the technology is still under research and development phase.

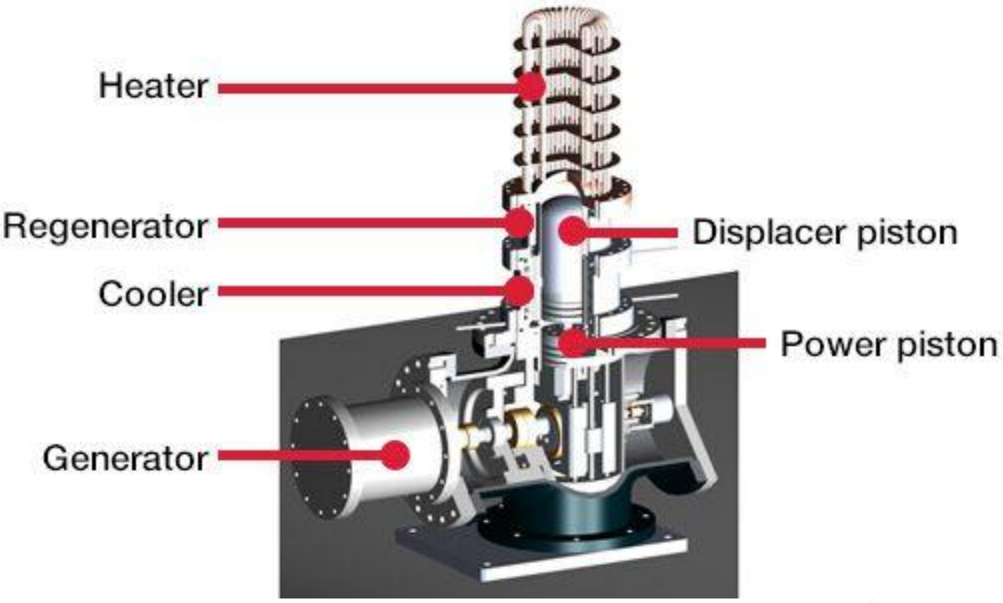


Figure 13: Schematic Diagram of the Stirling Engine (Source: Yanmar,2017)

2.3.6.3 Fuel Cells

Fuel cells are different to other electricity generating units in that it does not require a primer mover, the chemical energy is converted directly to electricity by electrochemical reactions occurring electrode surfaces in an electrochemical cell. Each electrochemical cell can generate electricity of a potential of 0.6 – 0.9 volts, and these cells can be connected in series to reach the required power output. The methane from the biogas has to be reformed to hydrogen prior to being fed into the fuel cell. The quality of the gas required for these applications are very high, as contaminants might poision the electrode surfaces which are often made of expensive materials. The overall effiency of the cell is 60%. The fuel cell has low maintenance costs compared to the other generating units as it has no moving parts, however, it has high capital costs and limited commercial applications, with a small number of plants mostly at a pilot scale.

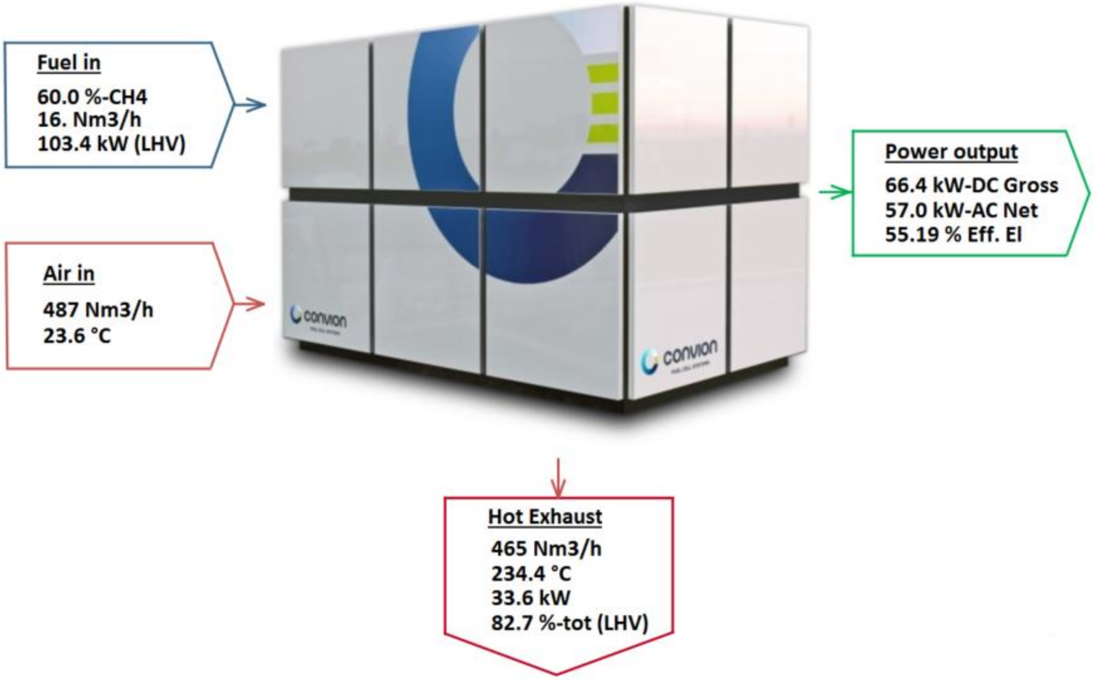


Figure 14: Fuel cell stack for electricity generation from biogas (source: Convion, 2017)

2.3.6.4 Microtubines

Microturbines are small, singleshaft, high speed gas combustion turbines with generating capacity that ranges from 25 to 500 kW. They are easy to handle, relatively low noise and vibration free. Their electrical generating efficiency is 15-30%, and exhaust gas leaving the unit at temperature of 200 – 300^{o}C, while low pressure stream or hot water can be generated. The microtubines consist of a compressor, combustion chamber and turbine. The biogas is compressed in the compressor and then channeled to the combustion chamber where it allowed to combust. The exhaust from the combustion chamber is allowed to expand in the turbine, and then the stored energy is converted into mechanical energy. The mechanical energy is then converted to electricity in the generator. The turbine is connected to both the generator and compressor of the biogas. To improve the generation efficiency, the temperature of the feed to the combustion chamber is raised and this can be achieved through the use of waste heat from engine. The microturbine has lower maintance cost and tolerant to high humidity and corrosive gases such as sulfur compounds, however, the unit has a high capital cost compared to engines.

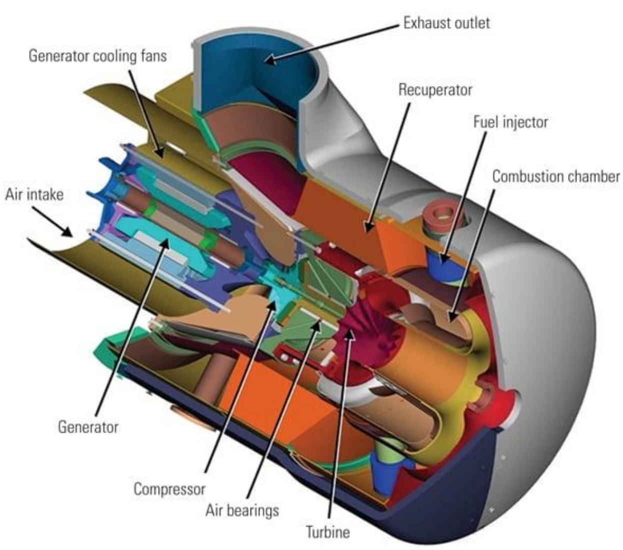


Figure 15: Microtubine for electricity generationn fror biogas (Source: Power, 2010)

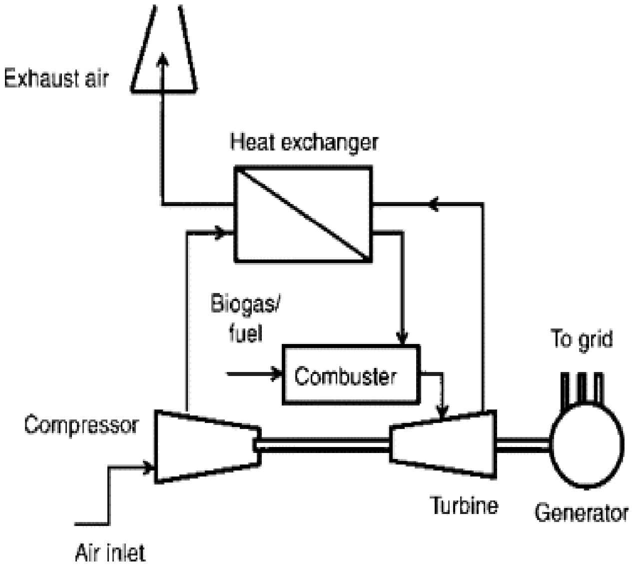


Figure 16: Schematic diagram of biogas microtubine (Source: Kuparaju & Rintala, 2013)

2.3.6.5 Gas Turbines

The operation of biogas turbines are different to microturbines, the difference is the size of the unit, the electrical generation and overall efficiency of the unit. Similar to the microturbines, they consist of compressor, combustion chamber and the turbine. The capacity of the generating unit ranges from 500 kW to 250 MW, with electrical generating effiency of 20 – 45% (Wellinger et al, 2013). The temperature of the exhaust leaves the turbine at temperature of 400 – 600 ^{o}C, this stream has high thermal energy that can be used for generation of low pressure steam (Deublein & Steinhauser, 2010 & Hall, 2010). Similar to microturbines, these turbines are resistant to humidity, corrosive gases and sulfur-containing compounds (Wellinger et al, 2013). Given the above mentioned benefits, it is of the authors' view that gas turbines are more suitable for generation of electricity at the proposed AD plant.

2.3.6.6 Design of Electricity Generation Unit

Similarly as per the work in Output 3, using the volumetric flowrate of methane (Q_{CH4}) generated in the digester, the electricity (E_{el}) generation potential was estimated using equation 45 (Cesaro & Belgiorno, 2021). The methane energetic potential (E_{CH4}) was assumed to be 10 kW h/m^3 as per the work of Ariunbaatar and co-workers (2014) and electrical efficiency (η_e) of the plant was assumed at 32.5%, an average of the lower and upper bound of the electrical efficiency which ranges from 25 – 40% for gas turbine (Wellinger et al, 2013).

$$E_{el} = E_{CH4} \times Q_{CH4} \times \eta_e \qquad (45)$$

The electricity generation potential will give the amount of electricity that will be generated daily, and dividing the figure by 24 hours, will give the power requirement of the generating unit. The power required was divided by two to give the power requirement for each turbine. Therefore, three units will be required where one will be used as stand-by generator. The design information is shown in table 4.

Table 7: Gas turbine design for the proposed 100TPD AD plant

Potential electricty Generation	47271.38	kWh/day
Electricity generation	1969.6	kW
Generation Unit Power	984.82(~1MW)	kW
Number of Generating Units required	3	Units

2.3.7 Heat Exchanger

The exhaust gas from the gas turbine leaves the engine at temperatures of 400 – 600 ^{o}C, the gas contains significant thermal energy which can be exploited as heat utility for any other heat requirement within the plant. Amongst other heat utility requirement within the plant, it is the generation of low-pressure steam for temperature maintenance in the anaerobic digester. The use of steam generated from the thermal energy of the digester will increase the efficiency of the plant, as compared to generated steam from other energy sources.

A shell & tube heat exchanger will be used to recover the thermal heat, water will flow on the shell-side and exhaust gas will flow in the tube side. The method for designing the heat exchanger followed is that of Hall (2012).

The heat (Q) that needs to be transferred from the waste exhaust gas to produce steam can be calculated using equation.

$$Q = c_p(T_{100oC} - T_{ambient}) + \Delta Hevaporation * m_{water} \tag{4641}$$

Where Cp is the heat capacity of water

T_{100oC} is the temperature at which the steam is generated

$T_{ambient}$ is the ambient temperature

$\Delta H_{evaporation}$ is the latent heat of evaporation

The area (A) of heat exchanger that is needed can be determined using equation:

$$A = \frac{Q}{U\Delta T_{mean}} \tag{4742}$$

Where U is the overall heat transfer co-efficient and ΔT_{mean} is the mean temperature log difference, and it can be calculated using equation .

$$\Delta T_{mean} = \frac{(T_{WGin} - T_{steam}) - (T_{WG\ out} - T_{Water})}{\ln \frac{(T_{WG\ in} - T_{Steam})}{(T_{WG\ Out} - T_{water})}} \tag{48}$$

The overall heat transfer co-efficient can be assumed to be $0.95h_i$, therefore, the film thermal conductivity on the tube side can be worked as follows:

$$\frac{h_i d_i}{k} = 0.023\ N_{Re}^{0.8} N_{Pr}^{0.4} \tag{49}$$

Where NRe is the Reynolds equation

Npr is the Prandtl number

$$N_{Re} = \frac{d_i \rho u}{\mu} \tag{50}$$

$$N_{Pr} = \frac{c_p \mu}{k} \tag{51}$$

k is the thermal conductivity of the gas

di is the diameter of the tube

u is the line velocity

µ is the dynamic viscosity

The tube size was chosen as 10mm, this such that the line velocity of 20.2 TPD of the flue gas is 36 m/s (Hall,2012). The flue gas properties were assumed to be similar to that of Pipe Flow Calculations (2021). The design of other parameters is shown in Table 8.

Table 8: Heat exchanger design

	Values	Unit
Exhuast gas flowrate	20.2	TPD
Density	0.516	kg/m^3
Volumetric Flowrate in each tube	0.458	m^3/s
Internal Diameter	0.01	M
Line Velocity in a tube	36	m/s
Temperature of Flue Gas	500	^{o}C
Heat Capacity	1171	J/kg K
Viscosity	0.0000347	Pa s
Gas thermal conductivity	0.0383	W/m^2 s
Prandtl Number	1.06	-
Reynolds Number	5289	-
Nusselt Number	22.4	-

Inside film coefficient	85.9	W/m^2 s
Overall Heat Transfer Coefficient	81.6	W/m^2 s
Temperature exit of waste gas	250	°C
Mean temperature stream	282.6	°C
Overall Heat Transfer Area	2.969	m^2
Length of tube	4	M
Surface area of each tube	0.126	m^2
Number of Tubes	163	tubes
Shell diameter	0.166	M

2.3.8 Composting Facility

A composting plant's design and implementation entails contributions from a variety of disciplines, including architecture, civil engineering, and those involved in technical facilities. It is critical to address and optimize these contributions during the planning of a composting plant, as this helps to minimize excessive construction costs and future plant maintenance costs. The ground conditions, site, building size and shape, and roof are all aspects that define the best and most cost-effective solution for the facility.

The facility's location must be in line with the local political strategy. Local governments typically engage waste management professionals to assess the quantity and quality of biodegradable garbage in a certain area in order to determine the strategy. Additionally, an economic analysis is usually conducted in order to identify regional markets for finished compost and assess their requirements. Once these facts have been gathered, it will be possible to determine if a centralized or decentralized notion can be implemented.

According to economic assessments, centralized solutions are often less expensive than decentralized options. However, economic considerations are not the only factors to consider while making a decision. Bidlingmaier, 2000 has reported that the centralized composting plants in Europe have capabilities ranging from 35,000 to 50,000 Mg per year, while decentralized plants have capacities ranging from 4,000 to 20,000 Mg per year. Over 50,000 Mg per year capacity facilities are out of scale in any landscape, at least in Europe. According to Satkofsky, 2001 the composting plants in the United States range in size from 1400 to 10,800 Mg per year. Centralized plant closer to cities can reduce the time needed to establish and build up the market needed for the compost. On the other hand the compost acceptability in agriculture can be greatly improved by decentralized approaches with a location adjacent to fields. This acceptability is required if the aim is to collaborate with agriculture and agroindustry as the primary investors and end consumers of compost, as well as enhance soil fertility in areas with low soil fertility. In rural areas, decentralized concepts are adopted. In urban regions with large population densities, centralized composting units are recommended for use.

The substrate should be stored in a structure that is sheltered from wind, rain, and snow on at least three sides. For the intensive phase of the composting process, a site near a farm in a rural location usually requires a cover; however, subsequent phases of the composting process could be conducted in the open air. The regions where germs could be discharged should be entirely contained, including up- and downloading, pre-treatment, the process area, and fine conditioning. Dust and germs collected from these places' air should be filtered in a biofilter and/or scrubber that must be integrated into the compost plant's architecture.

The plant's entrance road should wraps around the entire structure. In the event of a fire, the fire department's (brigade) access route should be far too close to the buildings. A prefabricated concrete tank should be used to holds the fire department's water supply. The building configuration should be simplified to one main building with enough windowa and the roof should be made of metal. The roof could be in the shape of waves, or it could be slightly slanted or flat. It could be safeguarded. The concrete flat or deep bunker has a well protected surface against mechanical damage. The floor must be designed with high and low locations to enable for dry cleaning of the bunker. The aeration system's pipes are usually installed in the processing area's floor. The processing area's floor is made up of prefabricated concrete plates that conceal the piping system. Perforations in these plates allow for airflow. A drainage and ventilation system is covered with a permeable sheet and wood chips on the floor of a processing building that is not accessible. Because condensation may cause the building's walls to become wet, the architect must carefully arrange for liquid drainage.

The digested waste will be dewatered using a screw press to achieve a dry matter concentration of at least 45%, then aerobically composted for 2 to 3 weeks. Temperatures of greater than 60°C are recommended during the first week of aeration, in order to kill any remaining pathogens. During this time, the dewatered cake will be turned into a well-stabilized compost that can be used in agricultural applications. The compost facility will generate about 2000 tons/year of compost and marketed to farms in the region.

Figure 17: Typical storage area for finished compost

Table 9: Design data of AD biogas plant unit

Parameter	**Value**
Type of digester	DRANCO SSHS
Temperature	55°C, Thermophillic
Hydraulic retention time [days]	20
Organic Loading Rate [kg VS/m3 day]	12.0
VS reduction [%]	43.2
Biogas content	45 CH_4, 39% CO_2 & 16% Moisture
VS content of influent [%]	90.2
TS content of influent [%]	45.6
VS Content of effluent [%]	52
TS content of effluent [%]	14.2
Material Flowrate [TPD]	95
Total Digestion Capacity [m^3]	7500

Unit	**Properties**
Physical pretreatment	Screens, magnetic separation, and rotating trommels
Digester feeding system	Screw conveyors
Sludge digester	2 tank, 3750 m^3 each, Stainless steel/Conical Bottom, Cylindrical
Sludge recirculation pump	1 X 67TPD screw conveyor pump 1 X 470 TPD screw conveyor pump 1 X 450 TPD screw conveyor pump
Heat exchanger (Digester heating system)	Single pass shell and tube Heat Exchanger tube internal diameter: 10mm Shell internal diameter: 166 mm Length: 4 meters Material of Construction: Stainless Steel on the tube side and carbon steel on the shell side
Chilling Unit	23 kW chilling/refrigeration unit
Electric power generator	3X1MW Biogas Turbine (Two operational and one on stand-by)
Biogas storage	Reinforced round-shaped shape/rubber membrane 1X 2000 m^3 Low Pressure Biogas Storage 1X 1300 m^3 Low Pressure Biogas Storage Material of construction: carbon steel

2.4 Listing of equipment and building required for the biogas plant

The designed biogas plant will include the following components:

- Administration buildings (offices for admistration staff)
- Control rooms with SCADA system for plant monitoring
- Laboratories for analysis of samples collected from the plants
- Toilets and showers for staff
- A structure for waste reception and short-term storage. This will be an aboveground tank.
- Waste pre-treatment for removing unwanted materials.
- Pre-treated OMFSW storage tank and pump for transferring the waste to the digester.
- A digester, which will be an aboveground steel tank.

- A biogas storage tank and biogas chiller for moisture removal along with other contaminats.
- Biogas turbine integrated with a compressor and recuperator, this will be connected an electrical generator by shaft for electricity generations.
- Interconnection equipment is required when biogas or generated electricity is used off site. All systems include a flare to safely burn surplus biogas.
- Liquid-solids separator, to remove and concentrate solids from the digester effluent and for nutrient and water recovery.
- Aerobic treatment (composting facility) to stabilize digestate cake prior to use as fertilizer or disposal
- Earth-moving equipment for handling of solid waste in open spaces (i.e waste reception area, composting facility, loading of residues into trucks for disposal at landfills, etc)

3 Considerations for the Integration into the Existing Value and Supply Chain (Deliverable 5.2)

The eventual implementation of anaerobic digestion will be something new and may disturb the solid waste management and energy supply systems already existent in Mauritius. In this context and to prevent any major implications/disturbances on the current systems, this Deliverable will consider the requirements and opportunities for integration of the biogas plant in the existing value chain for organic wastes (generation, transport and disposal), the supply chain for energy production and the integration of the use of digestate as organic fertiliser.

3.1 Organic waste value chain

As mentioned in Deliverable 2, most of the organic wastes generated from hotels, markets and households eventually end up at the transfer stations as commingled wastes prior to disposal at the Mare Chicose landfill. Since anaerobic digestion is suited only to organic wastes, this implies that only organic wastes such as food and yard wastes will need to be diverted to the biogas plant. As such, some sort of segregation will need to be carried out upstream of the biogas plant. Two opportunities for the segregation process exist namely: 1) source-segregation at the level of markets, hotels and households or 2) mechanical separation at the biogas plant. Between these two options, waste segregation at source is being privileged as this is already being envisaged by the Government of Mauritius in the western and northern regions of the island. Furthermore, source-segregation of wastes generates a higher quality waste material, be it organic wastes or recyclable materials (paper, plastics, etc.), which are thus more valuable. Similarly, the higher quality organic wastes yield higher methane as opposed to mechanically-sorted organic wastes and thus, represent more value for the biogas plant.

The implementation of waste segregation at source has several implications and requirements, as follows:

- Provision of additional bins at households, hotels and markets for the separate storage of organic wastes;
- Separate collection of the organic wastes by the Local Authorities, implying either additional collection vehicles or a change in their collection frequencies; and
- Proper sensitisation and awareness-raising campaigns to have a proper waste segregation at household level.

Based on the aforementioned implications and requirements, the organic waste management system will be called for a major change, as summarised in Figure 18.

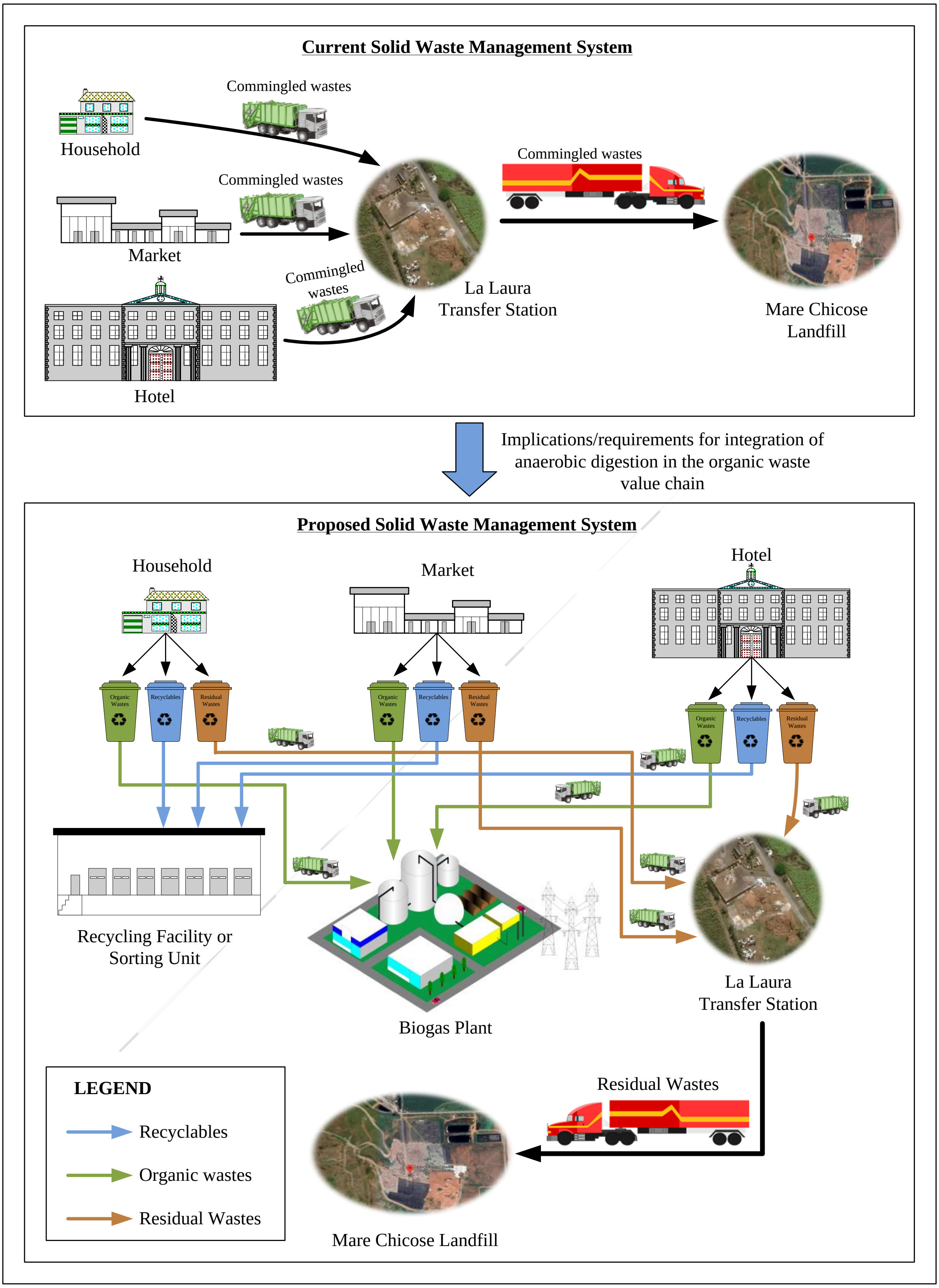


Figure 18: Solid waste management system

As proposed in Figure 18, organic wastes segregated at source will be separately collected and diverted to the biogas plant. Recyclable materials may be sent to a recycling plant or sorting unit but this will depend on the policy of Government while the residual wastes will be sent to a transfer station prior to disposal at the landfill. The choice of La Laura transfer station has been made in Figure 1 based on the outcomes from Deliverable 4. For markets, it is not expected that recyclable materials and residual wastes will constitute a major fraction. As such, the number of bins may be reduced to 2 (instead of 3) wherein the residual wastes and contaminated recyclables may be placed in a single bin and disposed at the transfer station. As for hotels, this shall be left to them as to how they will do the sorting at source.

3.2 Opportunities from a gender perspective

The integration of the gender aspect in the organic waste value chain involving anaerobic digestion will be mostly at household level. As mentioned in Deliverable 2, in most cases, the first person to handle wastes at household level is either a mother or a wife, that is, the female gender. As such, the involvement of the female gender in the implementation of waste segregation at source is seen as vital and key to the successful operation of the biogas plant. The effectiveness of the waste segregation process will have an escalating impact on the collection process and on the quality of organic wastes reaching the biogas plant. This will subsequently impact on the biogas and electricity production potential and on the viability of the whole project. As such, the female gender has a fundamental role in ensuring that waste segregation at household level is implemented efficiency and effectively.

3.3 Opportunities from a youth perspective

As for the youth aspect, this is mostly integrated in sensitisation and awareness-raising at the level of schools, colleges and universities. The sensitisation and awareness-raising must comprise both the aspects of waste segregation at source as well as basic understanding of the anaerobic digestion process particularly at tertiary level. The efficiency of waste segregation at source often depends on the younger members of a family who, in turn, bring about this change to the elderly people.

3.4 Energy supply chain

One of the main products of the anaerobic digestion process is biogas, which is combusted to produce electrical energy. Consequently, biogas plants often exist as off-grid systems while they can also be utilised to feed the grid network for base load power supply. Furthermore, electricity generation from biogas can be effectively used to bring stability to networks that rely on other intermittent sources of renewable energy. For the Mauritian context, it is being proposed that the electricity produced from the biogas plant be fed to the grid network to meet base load requirements.

As mentioned in Deliverable 4, the electricity produced from a biogas plant is normally at low voltage and transportation of this low voltage over long distances results in high losses. As such, the low voltage needs to be stepped up in a transformer (at a station in the vicinity of the biogas plant) prior to sending over high voltage lines to a transmission sub-station. With the sub-station of the Central Electricity Board (CEB), one of the requirements to feed the electricity from the biogas plant to the grid is to step it up to 66 kV through a step-up transformer. However, prior to this, an energy supply and purchase agreement (ESPA) or power purchase agreement (PPA) will need to be signed between the CEB and the operator of the biogas plant. With the biogas plant to supply base load power, it is thus expected that the CEB will eventually have a higher reserve margin and therefore require less external energy sources to meet its peak demand.

3.5 Digestate supply chain

Besides biogas, a by-product of the anaerobic digestion process is digestate. Digestate, as detailed out in Deliverable 3, has a huge nutrient content and can be effectively used as liquid organic fertilizer or in its solid form as compost. The use of the digestate from the biogas plant as liquid organic fertiliser or compost will require a proper sensitisation and awareness-raising campaign among planters as well as households to educate and encourage them to shift from chemical fertilizers. Planters, in particular, who consist of a significant proportion of the female gender will have a prominent role in the use of organic fertiliser and compost in crop cultivation at the expense of chemical fertilisers. Likewise, the younger generation needs to have the necessary knowledge about the several benefits of composting products on soil properties and crop cultivation and these need to be inculcated in both primary, secondary and tertiary education.

4 Summary/Recommendations of Deliverable 5

Deliverable 5 of the Technical Assistance comprised 1) a schematic design and inventory of the biogas plant and 2) an overview of integration requirements and opportunities into existing value and supply chain. Through deliverable 5, the key components constituting the biogas plant (based on the selected technology) have been listed while a preliminary mass and energy balance has also been prepared. Deliverable 5 also presented an overview of the requirements and opportunities for integration of the biogas plant into the existing organic waste value chain and the energy and digestate supply chains while also considering the aspects of gender and youth.

5 Reference

Al Seadi, T., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S. & Janssen, R., 2008. *Biogas handbook*. Esbjerg: University of Southern Denmark Esbjerg.

Ariunbaatar, J., Panico, A., Frunzo, L., Esposito, G., Lens, P. and Pirozzi, F., 2014. Enhanced anaerobic digestion of food waste by thermal and ozonation pretreatment methods. *Journal of Environmental Management*, 146, pp.142-149.

Brockmann HJ 1987. Taschenbuch fur den Maschinenbau/Dubbel. Beitz, W & Kuttner ISBN 3-540-18009-5

Cesaro, A. and Belgiorno, V., 2021. Anaerobic digestion of mechanically sorted organic waste: The influence of storage time on the energetic potential. *Sustainable Chemistry and Pharmacy*, 20, p.100-373.

Chavez-Vazquez, Mariana & Bagley, David. 2002. Evaluation of the performance of different anaerobic digestion technologies for solid waste treatment. Available at: <https://www.researchgate.net/publication/237809186_EVALUATION_OF_THE_PERFORMANCE_OF_DIFFERENT_ANAEROBIC_DIGESTION_TECHNOLOGIES_FOR_SOLID_WASTE_TREATMENT> [Accessed 3 November 2021].

Convion, 2021. *Superb performance with renewable biogas - Convion*. [online] Convion. Available at: <https://convion.fi/superb-performance-with-renewable-biogas/> [Accessed 3 November 2021].

De Baere, L., 2010. The Dranco Technology: A unique digestion technology for solid organic waste. Organic Waste Systems (OWS) Pub. Brussels, Beligium.

Schäfer, W., Lehto, M. and Teye, F., 2006. Dry anaerobic digestion of organic residues on-farm-a feasibility study.

Deublein, D. & Steinhauser, A., 2010. *Biogas from waste and renewable resources*. Weinheim: WILEY-VCH.

Elsharkawy, K., Elsamadony, M. & Afify, H., 2019. Comparative analysis of common full scale reactors for dry anaerobic digestion process. *E3S Web of Conferences*, 83, pp.1-5.

Hall, S., 2012. Boilers. *Branan's Rules of Thumb for Chemical Engineers*, pp.166-181.

HZ-Inova, 2021. *Kompogas® Anaerobic Digestion*. [online] Hitachi Zosen Inova AG. Available at: <https://www.hz-inova.com/renewable-gas/anaerobic-digestion/> [Accessed 3 November 2021].

Kaparaju, P. & Rintala, J., 2013. Generation of heat and power from biogas for stationary applications: boilers, gas engines and turbines, combined heat and power (CHP) plants and fuel cells. *The Biogas Handbook*, pp.404-427.

Khalil, T., Zhao, Q. & Maqsood, L., 2014. Energy from anaerobic digesters for water management: A case study of Pakistan. *IEEE Global Humanitarian Technology Conference (GHTC 2014)*.

Laizāns, A. & Vardanjan, R. 2017. Mathematical Modelling of Biogas Dehumidification by Using of Counter Flow Heat Exchanger. *Journal of Clean Energy Technologies*, 5(2), pp.170-173.

Le Pera, A., Sellaro, M., Migliori, M., Bianco, M. & Zanardi, G., 2021. Dry Mesophilic Anaerobic Digestion of Separately Collected Organic Fraction of Municipal Solid Waste: Two-Year Experience in an Industrial-Scale Plant. *Processes*, 9(2), p.213.

Maleki-Ghelichi, E. and Sharifi, M., 2017. Prioritize and choose the best process of anaerobic digestion to produce energy from biomass using analytic hierarchy process (AHP). *Geology, Ecology, and Landscapes*, 1(4), pp.219-224.

Pipe Flow Calculations, 2021. *Flue gas properties table*. [online] pipeflowcalculations.com. Available at: <https://www.pipeflowcalculations.com/tables/flue-gas.xhtml> [Accessed 2 November 2021].

Ranieri, L., Mossa, G., Pellegrino, R. and Digiesi, S., 2018. Energy recovery from the organic fraction of municipal solid waste: A real options-based facility assessment. *Sustainability*, *10*(2), p.368.

Rapport, J., Zhang, R., Jenkins, B. M. & Williams, R.B. 2014. Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste. Sacramento, CA: California Integrated Waste Management Board

Siemens, 2021. *S Series: SL Engines*. [online] siemens-energy.com Global Website. Available at: <https://www.siemens-energy.com/global/en/offerings/power-generation/gas-engines/sl-engines.html> [Accessed 2 November 2021].

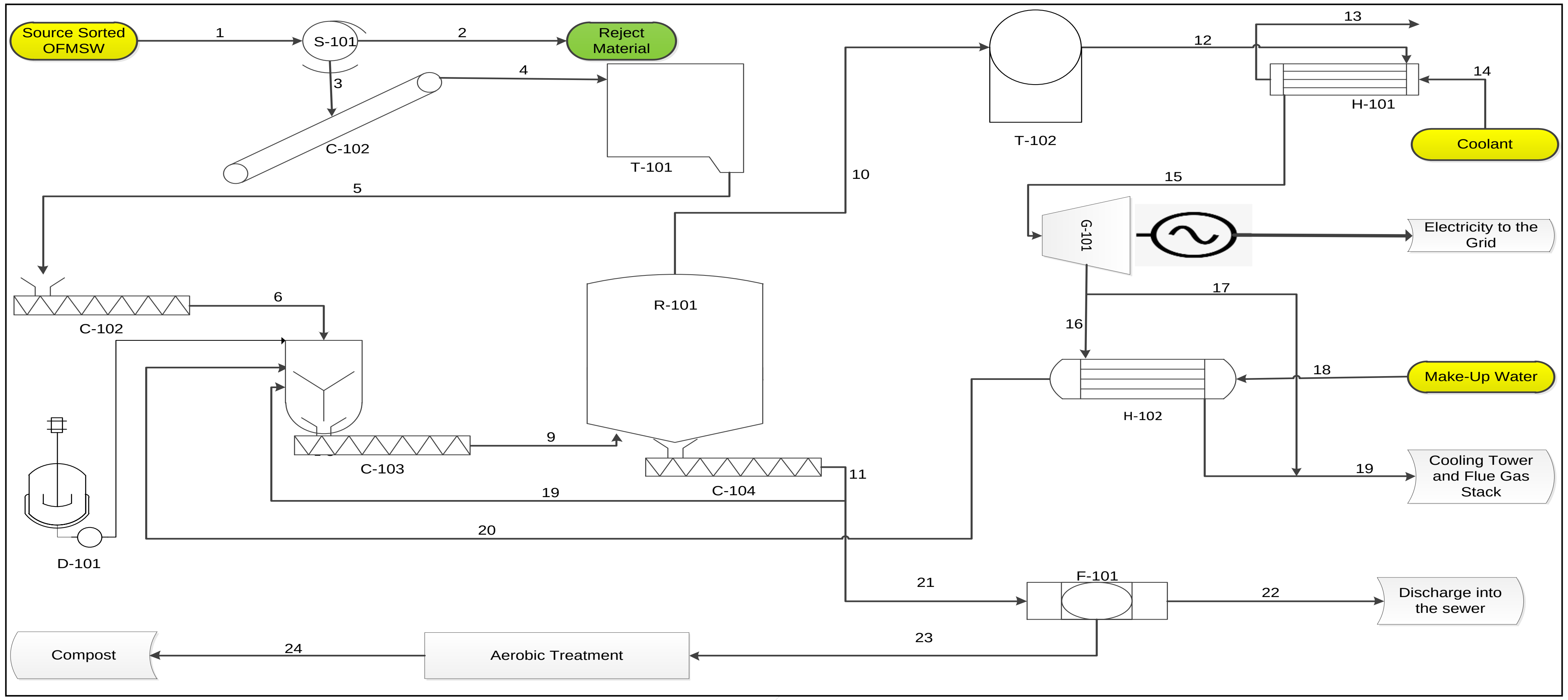
Valorga International, 2006. *Valorga's Anaerobic Digestion Process*. [online] Available at: <http://www.valorgainternational.fr/en/mpg3-128079--VALORGA-S-ANAEROBIC-DIGESTION-PROCESS.html> [Accessed 3 November 2021].

Vardanjans, R., Laizans, A., Jakovics, A. & Gendelis, S. 2015. Biogas specific heat capacity variations during upgrading. Engineering for Rural Development. 14. 372-376.

Wellinger, A., Murphy, J. P. & Baxter, D. 2013. *The Biogas Handbook*. Burlington: Elsevier Science.

Yanmar, 2021. *Exhaust Heat Recovery Stirling Engine*. [online] YANMAR. Available at: <https://www.yanmar.com/global/about/company/e-stir/technical_expertise/stirling_engine.html> [Accessed 3 November 2021].

Appendix A: Process Flow Diagram and Detailed Mass Balance



Unit	Rotary Screen (S-101)			Pretreated OFMSW Storage Tank (T-101)		Integrated Mixer Screw Pump (C-103)			AD Reactor (R-101)			Chiller (H-101)				Heat Exchanger (Low Pressure Steam Generator) (H-102)				Filter Press (F-101)		Aerobic Treatment Facility			
Stream No.	**1**	**2**	**3**	**4**	**5**	**6**	**19**	**20**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**21**	**22**	**23**	**24**	**25**	**26**
Mass [TPD]	100.0	5.0	95.0	95.0	95.0	95.0	570.0	2.3	667.3	39.3	627.9	35.8	-	-	35.4	20.2	15.2	2.3	15.2	57.9	39.6	18.3	1.8	0.5	7.55
TS [%]	45.63	45.63	45.63	45.63	45.63	45.63	14.2	-	18.59	-	14.2	-	-	-	-	-	-	-	-	14.15	-	44.80	75.00	52.00	55.3
VS [%]	41.49	41.49	41.49	41.49	41.49	41.49	7	-	12.19	-	7	-	-	-	-	-	-	-	-	7.35	-	0.23	65.00	0.23	0.22
VS/DM [%]	90.91	90.91	90.91	90.91	90.91	90.91	51.95	-	65.57	-	52	-	-	-		-				51.95		51.95	73.00	48.00	50.61
MC [%]	54.37	54.37	54.37	54.37	54.37	54.37	85.85	100	81.41	10.65	85.8	1.88	-	-	0.57	-	-	-	-	86	100	55	96	50	53
FS [TPD]	4.15	0.21	3.94	3.94	3.94	3.94	38.76	-	42.70	-	42.70	-	-	-	-	-	-	-	-	3.94	-	3.94	-	3.94	2.78
TS [TPD]	45.63	2.28	43.35	43.35	43.35	43.35	80.66	-	124.01	-	88.86	-	-	-	-	-	-	-	-	8.20	-	8.20	-	8.20	8.81
VS [TPD]	41.49	2.07	39.41	39.41	39.41	39.41	41.90	-	81.31	-	46.16	-	-	-	-	-	-	-	-	4.26	-	4.26	-	4.26	2.03
Water [TPD]	54.37	2.72	51.65	51.65	51.65	51.65	489.34	2.280104	543.27	4.19	539.08	0.67	-	-	0.20	-	-	-	-	49.74	39.64	10.10	1.70	0.25	5.1
Vol. Flowrate [Nm3/D]	-	-	-	-	-	-	-	-	-	32343	-	27974	-	-	27387	-	-	-	-	-	-	-	-	-	-
Dry Biogass Massflow[TPD]	-	-	-	-	-	-	-	-	-	35.15	-	35.15	-	-	35.15	-				-	-	-	-	-	-
CH4 [%] v/v	-	-	-	-	-	-	-	-	-	44.97	0	51.99	-	-	53.11	-	-	-	-	-	-	-	-	-	-
CO2 [%] v/v	-	-	-	-	-	-	-	-	-	38.93	0	45.01	-	-	45.97	-	-	-	-	-	-	-	-	-	-
Temperature [ºC]	23.3	23.3	23.3	23.3	23.3	23.3	55	100	55	55	55	23.3	-	-	5	500	-	23.3	-	23.3	23.3	23.3	60.0	60.0	60
Pressure [bar]	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	-	-	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	2.013	2.013	1.013

Appendix B: Properties of Exhaust Gas

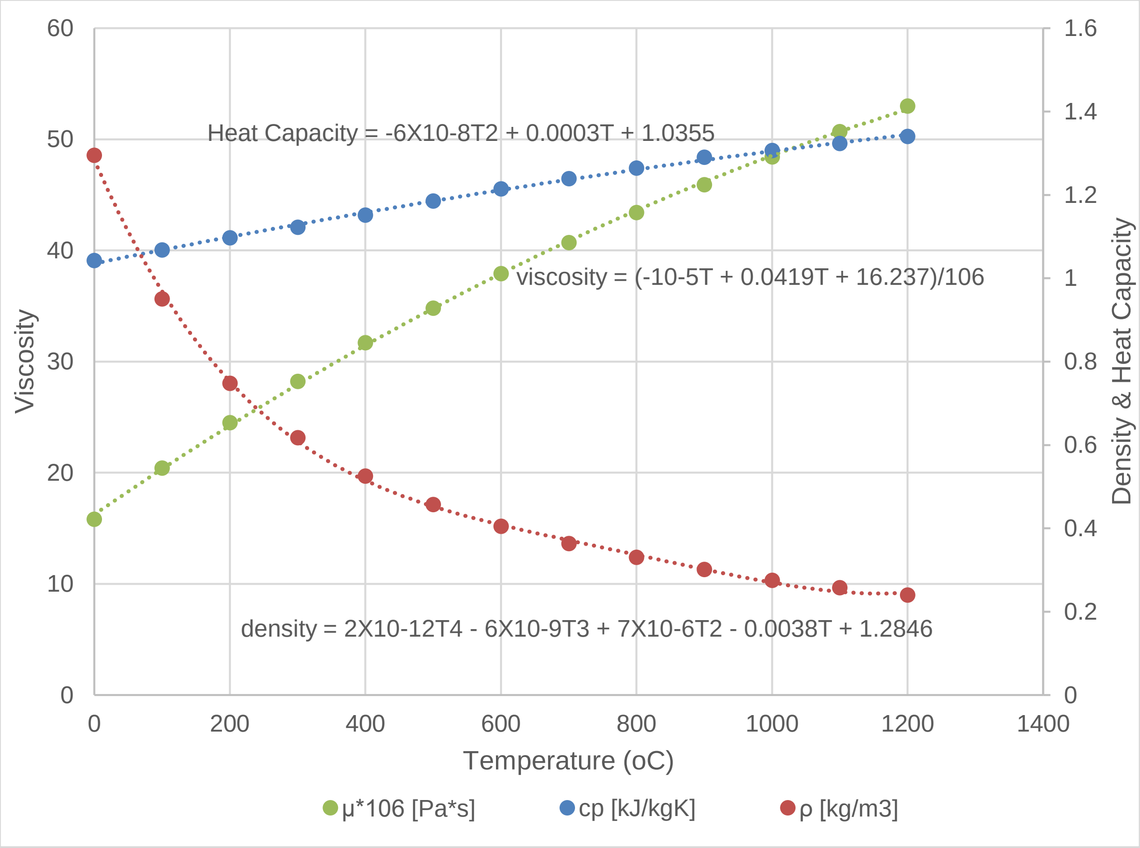


Figure B.1: Variation of turbine exhaust gas properties with changing temperature (Pipe Flow Caclulations, 2021)