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NUMBER OF CATTLE FOR COMMERCIALISING ELECTRICITY FROM CATTLE WASTE TO ENERGY TECHNOLOGY

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Abstract: We established the minimum number of cattle for commercializing electricity from the cattle wasteto-energy technology. By optimizing the cattle waste-to-energy technology for the various number of cattle, the minimum number of cattle was discovered. The number of cattle for commercializing electricity from cattle waste-to-energy technology is 60 dairy cows subject to co-digestion of manure and food waste, and the inclusion of a screw press. When digesting manure only, the minimum number of cattle is 130 cows.

Keywords: Renewable energy, cattle, electricity, WET, optimisation.

1 Introduction

This paper describes the solution to the problem of determination of the number of cattle at which cattle wasteto-energy technology (WET) become commercially applicable. The systems are considered commercially applicable if they have a positive net present value [1, 2]. The threshold of commercial viability is the number of cattle below which the NPV is negative. The number of cattle is determined by optimising the cattle WET for different number of cattle. The problem is solved by taking into consideration the following:

(i) co-digestion of manure and food waste,
(ii) cleaning of biogas,
(iii) electricity tariffs and
(iv) separation of digestate into solids and liquids.

Co-digestion increases the biogas yield.

Cleaning of biogas is done to remove hydrogen sulphide. Biogas contains hydrogen sulphide that corrodes internal combustion engines. Cleaning of biogas increases the lifetime of the engine-generator set. This reduces the replacement, operations and maintenance costs of the internal combustion engine. The cost of cleaning biogas has to be weighed against the cost of replacing the engine-generator set. Electricity tariffs determine the cost of electricity from the grid and therefore are considered in the optimisation.

The digester effluent can be separated into solids and liquids using a screw press. The solid effluent can be used in place of conventional animal bedding. Freund Dairy [3] and EL-VI Farms [4] are examples of farms that use digestate solids as animal bedding. Freund Dairy has 250 milking cows and saved USD 7000 [3] annually in animal bedding costs, by use of digestate solids as animal bedding. EL-VI Farms has 800 cows and saved USD 30,000 [4] annually by using digestate solids as animal bedding. Inclusion of a screw press to separate liquid and solid digestate, therefore gives the farm the option of saving on the cost of animal bedding.

2 The Study Area

Maddu is a town in Gomba district in the Central region of Uganda. The town is approximately 30 kilometres (19 mi), by road, northwest of Kanoni, the site of the district's headquarters [5]. The town is approximately 128 kilometres (80 mi) west of Kampala, the capital and largest city of Uganda [6]. Maddu is an agricultural community and Livestock forms the backbone of economic activity in the area. Milk and meat are important products produced by medium and small scale farmers in the area. The produce is sold locally in the popular Friday cattle markets and also marketed to Kampala. Prominent farms and ranches are located in areas of Kilasi (Katende Farm, Bitali family ranch), Kisozi YK Museveni farm and more towards Sembabule on one side, Buyanja and Kyayi on the other side.

Located at an elevation of none meters (0 feet) above sea level, Maddu has a Tropical rainforest climate (Classification: Af) [7]. The coordinates of Maddu are 0°12'58.0"N 31°40'02.0"E (Latitude: 0.216111; Longitude: 31.667222) [7]. The district's yearly temperature is 22.55ºC (72.59ºF) and it is -0.92% lower than Uganda's averages [7]. Maddu typically receives about 181.36 millimeters (7.14 inches) of precipitation and has 240.08 rainy days (65.78% of the time) annually [7]. Annual high temperature is 25.74ºC (78.33ºF), Annual low temperature is 17.5ºC (63.5ºF), Average annual precipitation is 181.36mm (7.14in), Warmest month is February (27.81ºC / 82.06ºF), Coldest Month is June (16.57ºC / 61.83ºF), Wettest Month is November (337.67mm / 13.29in), Driest Month is July (44.71mm / 1.76in), Number of days with rainfall (= 1.0 mm) 240.08 days (65.78%), Days with no rain = 124.91999999999999 days (34.22%), Humidity is 72.45% [8].

3 Related studies on Commercialising Waste to Energy Technology

This research on the number of cattle for commercial viability of cattle WET, uses the Tabu Search heuristic. The Tabu Search heuristic is suitable for solving the problem due to the complexity and non-linearity of the functions used to model the energy conversion processes, the problem's discrete optimisation variables and its nonconvex constraints. Modeling and optimisation of energy conversion systems has been done for purposes of economic analyses. These models base the analyses on energy flows and not the energy conversion processes. In [9], a multi-period mixed integer linear programming optimisation was applied to a district heating system. The objective of the optimisation was to minimise the cost of the heating system. The optimisation used mass and heat balance analyses to calculate the energy flows as opposed to thermodynamic models. Another technique used for optimisation of energy systems is MIND (Method for analysis of INDustrial energy systems), which is a decision support technique. The MIND method is used in [10] for optimisation of energy systems in a dairy industry and a pulp and paper mill. The energy systems were also modeled as energy flows and not as energy conversion processes. Similarly, in [11] a polygeneration plant fuelled by natural gas and renewable energy sources was designed and optimised. The energy generated from the biomass was determined from the specific fuel consumption of the biomass and the overall gasification efficiency. Mathematical modeling of the energy conversion processes was not used to determine the power output of the polygeneration plant. The system model used in the research being carried out is different in that it is based on the energy conversion processes in each of the system components. The models used to calculate the energy output from the conversion processes are: a digester, an internal combustion engine and an induction machine, a boiler and a heat exchanger. The ADM1 [12] and the GISCOD (General Integrated Solid Waste Co-Digestion) [13] models are used to calculate the energy conversion processes in the digester. The ADM1 was developed for prediction of biogas generated from anaerobic digestion of wastewater. The biomass waste to energy system model used for determination of the threshold number of cattle, considers co-digestion of manure and food waste. Prediction of biogas generated from codigestion of food waste and manure requires modification of some of the ADM1 parameters to allow for the different compositions of carbohydrates, proteins and lipids, and different hydrolysis rates. In [13] the GISCOD model that generates inputs to the ADM1 for co-digestion of different types of waste was developed. The GISCOD model is used together with the ADM1 to predict biogas generated from the co-digestion of manure and food waste. The internal combustion engine model used in the optimisation is obtained from the ADVISOR software [14]. The induction machine is modeled in the *dq* (direct-quadrature) synchronous reference frame and is based on the transient model of the induction machine [15]. The boiler and heat exchanger are modeled using heat transfer equations [16, 17].

The determination of the commercial viability of biomass waste to energy conversion systems is done in different ways, which include: payback period, overall production cost, NPV and profitability. In [18] the feasibility of electricity production from biogas on a pig farm used the payback period as an economic indicator. An economic and environmental assessment of the energetic valorization of organic material for a municipality in Quebec was studied in [19]. The payback period was also used as an economic indicator. Study [20] did a thermo-economic analysis of a biomass trigeneration plant. The study used the overall plant production cost as a measure of the cost effectiveness of the production process. The NPV was used as a measure of economic viability in [1], where an assessment of the technological development and economic potential of photobioreactors was done. The research undertaken uses NPV as an indicator of commercial viability. This is because the objective of the research is to determine the number of cattle at which the system becomes commercially viable. This threshold value is determined as the number of cattle below which the system’s NPV is negative.

4 Cattle WET Model for Determination of Number of Cattle for Trading of Electricity

This section describes the cattle WET model used in the determination of the number of cattle for commercial viability (Figure 1). The basic WET consists of a lagoon, a digester, a boiler, a propane tank and the electricity grid. These are the basic components of the system, because with these, heat and electricity can be provided to the farm. The heating load and electrical load demands can be met with these basic components. The lagoon is included in the basic system to allow for storage of manure. The propane tank is a backup fuel supply for the boiler, if insufficient biogas is generated. The other components of the system shown in Figure 1, which are discussed next, are optional. They include: an engine-generator set, a heat exchanger, co-digestion with food waste, a screw press and a biogas filter. These components are included in order to maximize revenue from the WET. The farmer can generate electricity for sale by including an engine-generator set in the system. A heat exchanger is used to capture exhaust heat which can be added to the heat generated by the boiler. Co-digestion of manure and food waste increase the yield of biogas. Tipping fees obtained from acceptance of off-site food waste increase revenue from the WET. The screw press separates the digester effluent into liquids and solids. The solids can be used as bedding for the animals, which saves the farm the cost of animal bedding. The separated liquid digestate can be spread on land as fertiliser. Use of the separated liquid digestate as fertiliser has not been included in the optimisation. This is because there are no case studies to quantify the cost savings from this practice, since the liquid digestate is used to supplement commercial fertilisers and is spread on land when required. Similarly, liquid digestate that is not separated into solids and liquids, is stored in lagoons and spread on land when required. Biogas contains hydrogen sulphide which corrodes the internal combustion engine. Cleaning biogas increases the lifetime of an engine-generator set and reduces replacement, operation and maintenance costs. Cleaning of biogas is an additional cost, and this has to be balanced with the cost of replacement of the engine-generator set. A biogas filter for cleaning the biogas is thus included in the system as an optional component. The decision on which of the optional components to include and how to operate the resulting system, is made using optimisation. A variable is attached to each of the components of the WET.

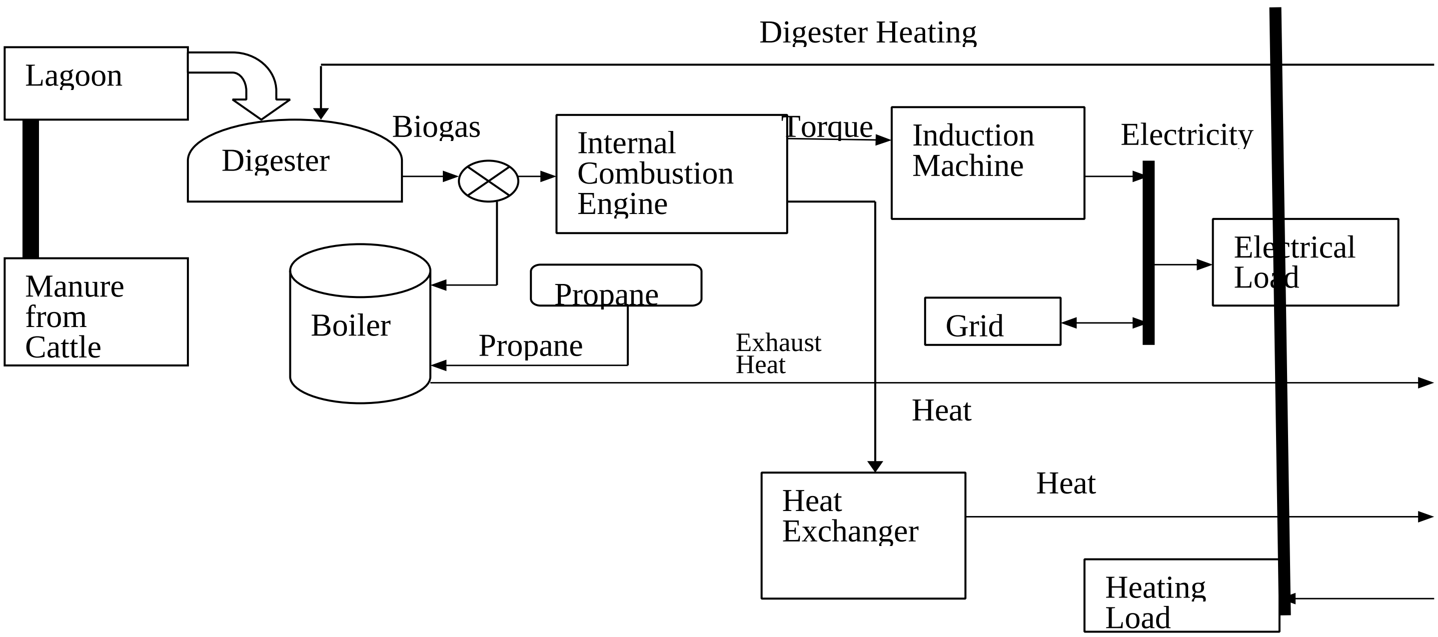

Figure 1: WET Model

5 Description of the Optimisation Problem

This section describes the optimisation problem. The statement of the optimization problem is given, followed by a description of the optimisation variables, inputs, and outputs of the WET. The formulation of the objective function and the constraints are also described.

5.1 Formulation of the Optimisation Problem

In solving the problem of the determination of the number of cattle at which the WET becomes commercially viable, the system has to be optimised. The optimisation problem consists in dimensioning the WET for a given manure input in a given time period $m \in M$. M is a set of the number of months in the multi-period dimensioning problem. The optimisation problem is expressed as a cost minimisation problem by:

$\min f^{\text{cost}}(u_1^m, u_2^m, u_3^m, u_4^m, u_5^m, u_6^m, u_7^m, u_8^m)$ for $m \in M$ for a number of cattle n

(1)

$$\text{subject to: } C_{\text{WET}}(u_1^m, u_2^m, u_3^m, u_4^m, u_5^m) \leq 0 \text{ for } m \in M,$$

(2)

$$\text{such that} : u_1{}^m \in \{0, 0.0001, 0.0002, \ldots, 0.0036\} \text{ for } m \in M\ kg/s,$$

(3)

$$u_2^m \in \{0, 0.01, 0.02, \ldots, 1\} \text{ for } m \in M$$

(4)

$$u_3^m \in \{1, 2, 3, \ldots, u_3^{m,max}\} \text{ for } m \in M \qquad \mathrm{m^3/day},$$

(5)

$u_4 \in$ (6)

$\{0, 60, 100, 120, 130, 135, 140, 145, 180, 200, 225, 230, 260, 300, 375, 400, 406, 450, 500, 600 \in M$ kW,

$$u_5^m \in \{0, 0.1, 0.2, \ldots, 2.8\} \text{ for } m \in M \qquad \mathrm{m^3/day}, \qquad (7)$$

$$u_6^m \in \{0, 0.1, 0.2, \ldots, 1\} \text{ for } m \in M \qquad \%, \qquad (8)$$

$$u_7^m \in \{0, 1\} \text{ for } m \in M, \qquad (9)$$

$$u_8^m \in \{0, 1\} \text{ for } m \in M, \qquad (10)$$

$$u_4^{m,max} = V_{\text{capacity\_lagoon}} n\, x_{\text{manure}} / n_{\text{days}}^m \text{ for } m \in M \quad \mathrm{m^3/day}, \qquad (11)$$

where u_1^m is the variable backup propane mass flow rate, u_2^m is the variable biogas sharing ratio, u_3^m is the variable volume flow rate of manure from the lagoon, u_4^m is the variable induction machine rating, u_5^m is the variable volume flow rate of food waste, u_6^m is the variable percentage increase in electricity tariffs, u_7^m is the variable that denotes the inclusion or exclusion of a screw press, u_8^m is the variable that denotes the inclusion or exclusion of a biogas filter, $V_{\text{capacity\_lagoon}}$ is the storage capacity of the lagoon, n is the number of cattle, x_{manure} is the volume flow rate of manure produced per cattle and n_{days}^m are the number of days. The bounds and the step sizes of the variables are determined from the inputs to the WET and literature review carried out. The maximum value of backup propane mass flow rate $u_3^{m,max}$ is obtained from the flow rate that meets the maximum heating demand, when the boiler is combusting propane only. This is also obtained using the maximum digester volume flow rate ($u_3^{m,max} + u_5^{m,max}$), since heat is needed to raise the temperature of influent waste to the digester's operating temperature. The variable u_4^m comprises of discrete values from typical engine-generator set ratings on farms. A value of 0 kW is included for the case where no electricity is generated and all the biogas is combusted in the boiler or flared. The maximum value of the variable, volume flow rate of food waste, $u_5^{m,max}$ is determined from the estimate of garbage generated by residential units.

The inputs to the WET are the number of cattle, n, the electrical load, d_{e}^m, and the heating load, d_{h}^m. The number of cattle are determined from typical dairy farms. The electrical load is derived from electrical loads on typical dairy farms [21]. The heating load of the dairy farms was obtained from a typical dairy farm. The digester's heating load was calculated from the heat required to maintain the operating temperature of the digester at its optimum, and to heat the influent manure. The outputs of the WET are electricity, y_1^m, and heat, y_2^m.

Table 1: Parameters of the Optimisation

Parameter	Description	Value
n_{dsays}^m	number of days in month m M (days)∈	Varies
n_{period}	number of periods for which interest rate will be charged (periods)	120
n_{year}	number of years over which the loan will be paid (years)	10
n_{repair}	number of years after which repairs of the engine are required (years)	5 (cleaned biogas) 2 (uncleaned biogas)
n_{cycle}	life cycle of the WET (years)	20
i_{rate}	interest rate of loan (%)	6
x_{rate}	power sizing exponent of the digester and engine-generator set	0.6 [22]
$c_{propane}$	unit cost of propane	1.98 USD/m^3 [23]
C_{lagoon_unit}	unit cost of an unlined lagoon (m3/day)	2.47 [24]
$C_{bedding}$	unit cost of animal bedding (USD/animal)	50 (cows) [25]
$C_{tipping}$	tipping fees (CAD/kg)	0.13 [26]
$x_{installation}$	factor to allow for system installation costs	1.15
δ_h	allowance for heating demand constraint (kW)	15
x_{manure}	volume flow rate of manure produced per animal of average weight 544kg/cow (m3/day)	0.0566 (cows) [27] 0.0497
x_{food}	maximum ratio of food waste in the digester	0.25 [28]
P_{rated}	power rating of induction machine (kW)	Varies
ω_{mech}	speed of engine-generator set (rad/s)	188.5
$V_{capacity\_lagoon}$	storage capacity of the lagoon (days)	varies with number of cattle
HRT	hydraulic retention time (days)	20
$LHV_{propane}$	lower heating value of propane (kJ/kg)	46,300 [29]
η_{HEX}	heat exchanger efficiency (%)	70
η_{boiler}	boiler efficiency (%)	70

T_{water}	temperature of water in the heat exchanger (◦C)	35
Max_iter	number of iterations for stopping condition of the Tabu Search	150

5.2 Objective Function

This section defines the objective function of the optimisation problem. Since the objective is to determine the number of cattle at which WET become commercially viable, the objective function is expressed as a cost

$$\min f^{\text{cost}} = \sum_{\text{m}=1}^{\text{M}} \left(C^{m}_{\text{capital}} + C^{m}_{\text{grid\_electricty}} + C^{m}_{\text{propane}} - C^{m}_{\text{bedding}} - C^{m}_{\text{tipping}} + C^{m}_{\text{catalyst}}\right),$$

for $\in M$ USD, (12) minimisation function:

where $C_{\text{capital}}{}^{m}$ is the monthly cost of capital of the biomass waste to energy conversion system, $C_{\text{capital}}{}^{m}$ is the monthly cost of grid electricity, C_{propane} is the monthly cost of propane, C^{m}_{bedding} is the monthly cost of animal bedding, C^{m}_{tipping} is the monthly revenue from food waste tipping fees and C^{m}_{catalyst} is the monthly cost of the catalyst used to clean the biogas. The following is an explanation of the derivation of the cost components of the objective function. The monthly cost of capital is obtained by amortization of the capital expenditure of the WET. The capital expenditure of the WET is calculated by:

$C_{\text{cost}} = (c_{\text{digester}} + c_{\text{eng\_gen}} + c_{\text{lagoon}} + c_{\text{boiler}} + c_{\text{biogas\_filter}} + c_{\text{screw\_press}})_{\text{installation}}$

USD, (13) where C_{cost} is the capital expenditure, c_{digester} is the cost of the digester, $c_{\text{eng\_gen}}$ is the cost of the engine-generator set and associated switchgear, c_{lagoon} is the cost of the lagoon, c_{boiler} is the cost of the boiler, c_{biogas} filter is the cost of the biogas filter, c_{screw} press is the cost of the screw press and $x_{\text{installation}}$ is a factor to allow for installation costs. Costs of the digester and the engine-generator set were obtained from the literature on existing WET [30, 31, 32]. Not all the costs of the different digester sizes and engine-generator set ratings were available from literature, thus cost estimating was done, by scaling the costs. The cost of the lagoon is calculated from the unit cost of an unlined lagoon, $c_{\text{lagoon\_unit}}$ (Table 1) [24]. The cost of boilers of different ratings was obtained from [33]. The cost of the bio-filter for cleaning biogas was obtained from [34]. The cost of a screw press is obtained from [35]. It is assumed that the WET will be financed by a loan taken over a n_{year} period. The monthly repayments are calculated using [22]:

where

$$C^{m}_{\text{payments}} = C_{\text{cost}} i_{\text{rate}} (1 + i_{\text{rate}})^{n_{\text{period}}} / ((1 + i_{\text{rate}})^{n_{\text{period}}} - 1) \text{ for } m \in M \text{USD}, \qquad (14)$$

C^{m}_{payments} is the monthly loan repayment, C_{cost} is the principle loan amount which is the capital expenditure on the WET, i_{rate} is the monthly interest rate and n_{period} is the number of periods for which interest will be paid over the n_{year} duration of the financing. When using biogas in an engine-generator set, the cost of replacement of the engine is significant and is included in the optimisation. It is significant because biogas contains hydrogen sulphide that corrodes the engine, which reduces the lifetime of the engine-generator set. Cleaning biogas reduces the frequency of replacement of the engine-generator set. When using cleaned biogas, the engine-generator set is replace every 5 years, and when using uncleaned biogas the replacement period is reduced to 2 years [18]. As such the annual cost of replacement is calculated by averaging the engine-generator set cost over n_{repair} years. The cost of replacement of the engine-generator set is added to the monthly loan repayment to obtain the monthly cost of capital $C^m_{capital}$.

The monthly cost of grid electricity $C^m_{grid\_electricity}$, is calculated [36]. Rate G is the general rate of electricity supplied. A WET has parasitic electric loads from the equipment used to run the system. These loads include: a mixer, a screw press, a food shredder and a recirculating pump. These parasitic loads are not considered under dwelling or farm loads, as they are used to generate electricity for sale. Depending on the size of the WET, these parasitic loads may exceed 10 kW, and would require a separate meter, billed at the general rate.

The monthly cost of propane, $C^m_{propane}$, is calculated from the unit cost of propane, $c_{propane}$, obtained from [23] and given in Table 1. Inclusion of the screw press in the system saves the farm the cost of animal bedding. The avoided cost of animal bedding is calculated from the unit cost of bedding per animal, $c_{bedding}$ [25, 37] (Table 1). The monthly revenue from tipping fees, *Cm* tipping, included in the objective function is calculated from an estimate of the tipping fees [26] (Table 1).

The monthly cost of the biogas filter used for cleaning biogas, $C^m_{catalyst}$, was obtained from [38].

5.3 Constraints

The optimisation of the WET is done subject to the constraints C^m_{WET} $(u^m_1, u^m_2, u^m_3, u^m_4, u^m_5)$, for $m \in M$, defined by (15), (16), (17), (18), (19) and (20). The following is an explanation of the derivation of the constraints. The manure from the animals is stored in a lagoon. The volume flow rate of manure from the lagoon into the digester,

u^m_3, varies from month to month. Constraint (15) is set to ensure that the net volume of manure in the lagoon is not negative. With Constraint (15), the volume of manure that goes into the lagoon in month *m*, should not be greater than the sum of the volume of manure that was in the lagoon the previous month, and the volume of manure from the animals, in month *m*. In addition the volume of manure in the lagoon should not be greater than the storage capacity of the lagoon. Constraint (16) ensures that the food waste added to the digester is within a ratio, x_{food}, of the total volume of waste in the digester [28]. Constraint (17) is set to ensure that the total volume of waste in the digester is not greater than the volume of the digester. The digester model uses non-linear differential equations to model the anaerobic digestion processes. The differential equations can be found in [12]. The biogas generated is shared between the internal combustion engine and the boiler. The variable $u_2{}^m$ determines the sharing of biogas. Combustion of biogas in the internal combustion engine generates an output torque. The output torque is obtained by applying the Newton-Raphson method to a two dimensional linear interpolation function, multiplied by the available torque. The details of the functions, ICE used in the internal combustion engine model can be found in [14]. The internal combustion engine is coupled to an induction machine of rating,

u^m_4, that generates output electricity, y^m_1. The induction machine is modeled using non-linear differential equations detailed in [15]. The electricity generated is a function of the output torque, which is in turn a function of the mass flow rate of biogas to the internal combustion engine. Constraint (18) is therefore set to limit the mass flow rate of biogas to not more than what is required to generate rated power of the induction machine. The heat produced by the boiler is calculated from the mass flow rate of biogas and propane to the boiler, and the LHV of biogas and propane. Exhaust heat captured by the heat exchanger is calculated from the temperature and the mass flow rate of the exhaust gases. Constraint (19) is set to ensure that the heat output of the WET meets the heating demand of the farm and the digester. Constraint (20) is set to ensure that the heat to be generated by the boiler is not greater than the boiler rating. The contribution of the heat captured by the heat exchanger is subtracted from the heat output of the boiler in formulation of Constraint (20). The boiler rating is calculated by a non-linear equation.

$$0 \leq \left(x_{\text{manure}} n n_{\text{days}}^{m} + V_{\text{lagoon\_manure}}^{m-1} - u_3^m n_{\text{days}}^{m}\right) \leq V_{\text{lagoon\_storage}} x_{\text{manure}} n_{\text{herd}}, \quad (15)$$

$$0 < u_{5m} \leq u_{3m}\, x_{\text{food}} / (1 - x_{\text{food}}), \quad (16)$$

$$(V_{\text{D}} - (u_3^m + u_5^m)\text{HRT}) \geq 0, \quad (17)$$

$$\left(u_4^m / \omega_{\text{mech}} - \text{ICE}\left(\text{LHV}_{\text{biogas}}^{m}, \omega_{\text{mech}}, (1 - u_2^m) m_{\text{biogas}}^{m}\right)\right) \geq 0, \quad (18)$$

$$d_{hm} \leq (\eta_{HEX} m_{\text{exh}m}\, cp_{\text{exh}m}\, (T_{\text{exh}m} - T_{\text{water}}) + (u_{1m} LHV_{\text{propane}} + u_{2m} m_{\text{biogas}m} \quad LHV_{\text{biogas}m} \quad)_{\text{boiler}})$$
$$\leq (d_{\text{h}}{}^{m} + \delta_{\text{h}}), \quad (19)$$

$$\left(b_r - d_{\text{h}}^{m} + \eta_{\text{HEX}} m_{\text{exh}}^{m} cp_{\text{exh}}^{m} (T_{\text{exh}}^{m} - T_{\text{water}})\right) \leq 0, \quad (20)$$

for $\in M$

where x_{manure} is the volume flow rate of manure produced per animal, n_{herd} is the number of cattle, n_{days}^{m} is the number of days, $V_{\text{lagoon\_manure}}^{m-1}$ is the volume of manure in the lagoon, V_3^m is the variable volume flow rate of manure from the lagoon, $V_{\text{lagoon\_storage}}$ is the storage capacity of the lagoon, $V_3^m$is the volume flow rate of food waste, x_{food} is the maximum ratio of food waste in the digester, V_{D} is the volume of the digester, HRT is the hydraulic retention time of the digester, *um*4 is the power rating of the induction machine, ω_{mech} is the speed of the internal combustion engine, ICE is the function used to calculate the torque output of the internal combustion engine, LHV_{biogas}^{m} is the lower heating value of biogas, u_2^m is the variable biogas sharing ratio, m_{biogas}^{m} is the mass flow rate of biogas, d_{h}^{m} is the heating demand, η_{HEX} is the efficiency of the heat exchanger, m_{exh}^{m} is the mass flow rate of the exhaust gases, $cp_{\text{exh}}^{m}$is the specific heat capacity of the exhaust gases, $T_{\text{exh}}^{m}$is the temperature of the exhaust gases, T_{water} is the temperature of water, *um*1 is the mass flow rate of backup propane, *LHV m* propane is the lower heating value of propane, η_{boiler} is the efficiency of the boiler, δ_h is an allowance for the heating constraint and b_r is the boiler rating.

6 The NPV of the WET

The NPV of the WET is used to determine its commercial viability. The NPV is calculated by [39]:

$$\mathrm{NPV} = \sum_{t=0}^{n_{cycle}} A(1 + i_{rate})^{-t} \quad \mathrm{USD}, \tag{21}$$

where NPV is the net present value of the WET, n_{cycle} is the life cycle of the WET in years, t is the year under consideration, A_t is the annual cash flow and *i*rate is the interest rate. The herd sizes below which the NPV of the WET becomes negative (threshold herd sizes) was found to be 60 cows when co-digesting manure and food waste. This is subject to the inclusion of food waste and a screw press in the WET. The food waste should be a maximum of 25% of the total waste in the digester. The threshold herd size with digestion of manure only was found to be 130 cows. **7 Conclusion**

In this paper, we have illustrated how the Tabu Search Algorithm can be used to specify the number of cattle at which a WET becomes commercially viable. The WET becomes commercially viable at a herd size of 60 dairy cows subject to co-digestion of manure and food waste, and inclusion of a screw press. When digesting manure only, the threshold herd size is 130 cows. In calculating the heat output of the heat exchanger, the temperature of the water circulating in the heat exchanger was set to 35^{O}C, which is the same value as the operating temperature of the digester. The typical temperature difference between the manure in the digester and the water circulating in the heat exchanger is 7.2^{O}C [40]. Use of the same value of temperature means that in practice there is no heat transfer from the water circulating in the heat exchanger to the manure in the digester. The calculated heat output of the heat exchanger is greater than what is practical. This is because the heat output of the heat exchanger was calculated from the temperature difference between the exhaust gases of the engine-generator set, and the water circulating in the heat exchanger. The transfer of this heat to the manure was not calculated, as it was assumed that the heat from the exhaust gases is available for transfer to the manure. This impacts the cost of propane which is a cost component of the objective function, of the optimisation problem. More propane than what was calculated would be required. This discrepancy does not affect the electricity generated, as during the optimisation priority was given to the use of biogas for generation of electricity. If the heating demand could not be met by the combustion of biogas in the boiler and the heat from the exhaust gases, propane was combusted in the boiler. Similarly, the discrepancy does not affect the threshold number of cattle. This is because the magnitudes of the cost of propane are very low in comparison to the magnitudes of the other cost components of the objective function.

References

Holtermann, T., & Madlener, R. (2011). Assessment of the technological development and economic potential of photobioreactors. Applied energy, 88(5), 1906-1919.

Rezvani, S., Saadaoui, I., Al Jabri, H., & Moheimani, N. R. (2022). Techno-economic modelling of high-value metabolites and secondary products from microalgae cultivated in closed photobioreactors with supplementary lighting. Algal Research, 65, 102733.

Wright, P., & Ma, J. (2003). Anaerobic Digester at Freund Dairy.[Accessed 17 July 2022]. [Online]. Available: http://www.manuremanagement.cornell.edu/Pages/Topics/General-Docs\/C%ase Studies/Freund Case Study.pdf

Wright, P. “Anaerobic Digester at EL-VI Farms: Case Study,” 2004, [Accessed 17 July 2022]. [Online]. Available: http://www.manuremanagement.cornell.edu/Pages/Topics/General-Docs\/C%ase Studies/ELVI Case Study.pdf

Globefeed.com (GF). (2022 a). "Road Distance Between Kanoni And Maddu With Map". Globefeed.com (GFC). Retrieved 11 August 2022.

Globefeed.com (GF). (2022 b). "Map Showing Kampala And Maddu With Route Marker". Globefeed.com (GFC). Retrieved 11 August 2022.

Google, (11 August 2022). "Location of Maddu at Google Maps" (Map). Google Maps. Google. Retrieved 11 August 2022.

Weather & Climate. (2022). https://tcktcktck.org/uganda/gomba/maddu. Accessed 19 August 2022

J. Sandberg, M. Larsson, C. Wang, J. Dahl, J. Lundgren, “A New Optimal

Solution Space Based Method for Increased Resolution in Energy System Optimisation,” Applied Energy, vol. 92, pp. 583–592, 2012.

M. Karlsson, “The MIND method: A Decision Support for Optimization of Industrial

Energy Systems Principles and Case Studies,” Applied Energy, vol. 88, pp. 577–589, 2011.

C. Rubio-Maya, J. Uche-Marcuello, A. Mart´ınez-Gracia, A.A. Bayod-R´ujula, “Design Optimization of a Polygeneration Plant Fuelled by Natural Gas and Renewable Energy Sources,” Applied Energy, vol. 88, pp. 449–457, 2011.

Batstone, D. J., Keller, J., Angelidaki, I., Kalyuzhnyi, S. V., Pavlostathis, S. G., Rozzi, A., ... & Vavilin, V. A. (2002). The IWA anaerobic digestion model no 1 (ADM1). Water Science and technology, 45(10), 6573.

U. Zaher, R. Li, U. Jeppsson, J. Steyer, S. Chen, "GISCOD: General Integrated Solid Waste Co-Digestion model," Elsevier Water Research, vol. 43, pp. 2717-2727, 2009.

National Renewable Energy Laboratory, "Advanced Vehicle & Fuels Research," 2002, [Accessed July 20 2022]. [Online]. Available: http://www.nrel.gov/vehiclesandfuels/vsa/related links.html#advisor

N. Mohan, Advanced Electric Drives Analysis, Control and Modeling using Simulink. MNPERE, Minneapolis, 2001, pp. 3–1, 3–26.

C.W. Turner, S. Doty, Energy Management Handbook, 6th ed. Fairmont Press, Inc., 2006, pp. 193–207.

Makamure, F., Mukumba, P., & Makaka, G. (2021). An analysis of bio-digester substrate heating methods: A review. Renewable and Sustainable Energy Reviews, 137, 110432.

S. Pipatmanomai, S. Kaewluan, T. Vitidsant, "Economic Assessment of Biogasto-Electricity Generation System with H_2S Removal by Activated Carbon in Small Pig Farm," Applied Energy, vol. 86, pp. 669–674, 2009.

P. Morin, B. Marcos, C. Moresoli, C.B. Laflamme, "Economic and Environmental Assessment on the Energetic Valorization of Organic Material for a Municipality in Quebec, Canada," Applied Energy, vol. 87, pp. 275–283, 2010.

Z.T. Lian, K.J. Chua, S.K. Chou, "A Thermoeconomic Analysis of Biomass Energy for Trigeneration," Applied Energy, vol. 87, pp. 84–95, 2010.

R. MacDonald, C.L. Gibbs, "Electricity Deregulation," in London Swine Conference - Conquering the Challenges, 11th - 12th April, 2002.

A.J. Szonyi, R.G. Fenton, J.A. White, M.H. Agee, K.E. Case, Principles of Engineering Economic Analysis, revised canadian ed. Wall & Emerson, 2000, pp. 38–39.

U.S. Energy Information Administration, "Weekly Heating Oil and Propane Prices (October-March)," [Accessed July 17 2022]. [Online]. Available: http://www.eia.gov/dnav/pet/pet pri wfr dcus nus w.htm

M.A. Moser, K.F. Roos, "AgSTAR Program: Three Commercial Scale Anaerobic Digesters for Animal Waste, Making a Business from Biomass," in Proceedings of the 3rd Biomass Conference of the Americas, Elsevier Science Inc., Tarrytown, NY., 1997.

The Minnesota Project, "Anaerobic Digesters Farm Opportunities and Pathways," [Accessed 20 July 2022. [Online]. Available: http://www.mnproject.org/pdf/Anaerobic%20Digesters%203-2-11-HR.pdf

R´egie intermunicipale de gestion des d´echets des Chutes-de-la-Chaudi`ere, "Services offerts," [Accessed 20 July 2022. [Online]. Available: http://www.chaudiere.com/regie-dechets/services.html

E.M. Barker, H.P. Neumann, "Sizing Dairy Manure Storage Facilities. British Columbia Ministry of Agriculture and Food. Farm Structure Fact Sheet." [Accessed 18 July 2022]. [Online]. Available: http://www.agf.gov.bc.ca/resmgmt/publist/300Series/383100-2.pdf

Ontario Ministry of Agriculture, Food and Rural Affairs, "Energy Yields from a Farm-Based Anaerobic Digestion System," 2011, [Accessed 18 July 2022]. [Online]. Available: http://www.omafra.gov.on.ca/english/engineer/facts/enyields.htm#8

National Gas, "Characteristics of LP Gas," [Accessed 20 June 2022]. [Online].

Available: http://www.nationalgasco.net/portals/0/Characteristics%20of%20LPGas.pd%f

P. Wright, J. Ma, "Anaerobic Digester at Spring Valley Dairy: Case Study," 2003, {Accessed 18 July 2022]. [Online].

J. Pronto, C. Gooch, "Anaerobic Digestion at Ridgeline Dairy Farm: Case Study," [Accessed 18 July 2022]. [Online]. Available: http://agrienvarchive.ca/bioenergy/download/RL case study rev1.pdf

J.H. Martin, "An Evaluation of A Mesophilic, Modified Plug Flow Anaerobic Digester

for Dairy Cattle Manure," 2005, [Accessed 23 July 2022]. [Online].

Available: http://www.epa.gov/agstar/documents/gordondale report final.pdf

Hot Water Boiler and Recirculating Pump Selection Chart and Distributor Price, [Accessed 23 July 2022] [Online]. Available: http://www.pumpsandpressure.com/docs/tech/Hot-Water-Boiler-SelectionG%uide.pdf

B.D. Roloson, N.R. Scott, K. Bothi, K. Saikkonen, S. Zicari,"Biogas Processing," 2006, [Accessed 18 July 2022]. [Online]. Available: http://www.manuremanagement.cornell.edu/Pages/General Docs/Reports\/%NYSERDA final report Biogas Processing.pdf

C. Gooch, J. Pronto, "Anaerobic Digestion at A.A. Dairy: Case Study," 2008, [Accessed 20 June 2022]. [Online]. Available: http://www.manuremanagement.cornell.edu/Pages/Topics/General Docs/Case% Studies/AA Case study.pdf

ELECTRICITY RETAIL TARIFFS FOR QUARTER ONE 2022https://www.umeme.co.ug › 2022/01 › [Accessed 19 August 2022]

D. Reich, J. Kliebenstein, "Economics of Breeding, Gestating and Farrowing Hogs in Natural Pork Production Financial Comparison," [Accessed June 18 2022]. [Online]. Available: http://www2.econ.iastate.edu/research/webpapers/paper 12613.pdf

D. Heguy, J. Bogner, "Cost-Effective Hydrogen Sulfide Treatment Strategies for Commercial Landfill Gas Recovery: Role of Increasing C&D (Construction and Demolition) Waste," 2011, [Accessed July 18 2022]. [Online]. Available: http://www.merichem.com/resources/technical papers/municipal landfil%ls.\php

J.A. White, K.E. Case, D.B. Pratt, Principles of Engineering Economic Analysis, 5th ed. John Wiley & Sons. Inc., 2009, pp. 55, 61.

Walker Process Equipment, "Anaerobic Digester Heating," 2012, [Accessed 20 July 2022]. [Online]. Available: http://www.walker-process.com/pdf/ 2012 Anaerobic Digester Heating.p%df