

Simulation of Electricity Generation from Biogas for Ugandan Rural Community

Aldo Okullo^{*}, Noah Tibasiima, Joshua Barasa

Department of Chemistry, Kyambogo University, Kampala, Uganda

Email address:

okulloapita@yahoo.com (A. Okullo), ntibasiima@gmail.com (N. Tibasiima), brsjosh@gmail.com (J. Barasa)

^{*}Corresponding author

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Abstract: One of Uganda's greatest hindrances to development is lack of access to energy. In rural areas where about 84% of the population lives, access to electricity is less than 2% a situation that leaves rural communities to continue depending on biomass based fuels in forms of firewood and charcoal. This paper proposes the utilization of biogas to generate off-grid electricity for the rural community. A simulation of electricity generation from biogas for Ugandan rural community using Aspen HYSYS V8.8 for computational modeling was developed on thermodynamic concepts. Two systems were considered; a gas-turbine (GT) only system and a GT-with steam turbine (ST) in the bottom cycle, based on 71% methane - 29% carbon dioxide as inlet biogas composition. The results obtained showed that it is possible to obtain 2.5MW of electricity using a gas turbine (GT) only system and an additional 1MW when a combined cycle system (GT-ST) is considered. An analysis of the exhaust gases showed that there are negligible amounts of gaseous pollutant though not in amounts that could constitute environmental threats when disposed to the atmosphere. In order to meet the system's need, a cattle head count of 13740 is estimated to be maintained for a daily supply of 670 tons of cow manure.

Keywords: Biogas, Biomass, Power Generation, Simulation

1. Introduction

Uganda is blessed with abundant natural resources that are fairly distributed throughout the country; the fertile land, the minerals and the diverse flora and fauna resources. Most of these resources are renewable in nature and have the potential, if fully exploited, to provide for the energy demand of a 36.6 million population (mid 2016) growing at about 3% annually [1]. However with a poverty rate at 19.7% [1] among many other factors, these resources are underutilized leaving the landlocked East African nation among the poor countries in Africa with a per capita energy consumption estimated at 39 kg oil equivalent (kgOE) compared to Kenya's 80 kgOE and Italy at 2959 kgOE [2]. One of Uganda's greatest hindrances to development is lack of access to energy and this keeps the nation in a vicious cycle of poverty since access to energy is a driving force to eliminate poverty [3, 4]. About 90% of the country's energy matrix is dominated by biomass based sources portioned into firewood (78.6%), charcoal (5.6%) and

crop residues (4.7%). These are used for cooking and water heating in rural areas, most urban households, institutions, and commercial buildings. Currently, charcoal consumption in Uganda is estimated at 580,000 tons per annum with a biomass equivalent of about 6 million tons of wood, based on the conversion efficiency of 10% for the charcoal stoves in use. The per capita consumption of firewood in rural and urban areas is 680kg/yr and 240kg/yr respectively. Per capita charcoal consumption is 4kg and 120kg in rural and urban areas respectively [5], charcoal being a commodity for sale to the urban from the rural communities. Electricity contributes only 1.4% to the national energy balance while petroleum products, which are mainly used for vehicles and thermal power plants, account for the remaining 9.7% [5].

The country is currently in the development of her 6.5 billion barrel of oil fields and the establishment of a 60,000 bpsd refinery to supplement its energy requirements. A planned 100MW natural gas fired thermal power station is also in the pipeline. Power generation for urban industries is heavily dependent on fossil fuel consumption whereas rural industries

depend on biomass utilization. However as fossil fuel depletion will become a reality later in future and the destruction to the environment due to deforestation, soil erosion and greenhouse gas (GHG) emissions, the country has no option but to start looking into ways of exploiting renewable resources of energy.

Electricity is critical for Uganda to drive her economy in order to attain the growth trajectory and socio-economic transformations she needs. However, the installed electricity power plant capacity is only at 895.5MW of which 20.4% is for household supply and this is still very low [1] compared to Kenya's 36% [6] and yet ironically Kenya imports 30MW from Uganda.

In rural areas where about 84% of the population lives, access to electricity is less than 2% [2, 7] mainly due to the prohibitive cost of connecting remote and isolated areas to the national grid [5]. The national grid is supplied majorly by hydro-power (82%) and thermal (10%) with mini-hydro at (5%), and cogeneration (3%) [8]. The situation is worsened by the lengthy drought, inadequate investment in low cost generation capacity and a relatively high load growth.

To alleviate this problem, a search into the utilization of decentralized off-grid renewable energy systems to support Uganda in meeting its SE4All targets by 2030 has been initiated by the government through the Renewable Energy Policy 2007 (REP-2007). The goal is to increase, in significant proportions, the contribution of Renewable Energy to the energy matrix from 4% to 61% by the year 2017 however this is currently only at about 52%. The government has set out various strategies to improve energy access to the rural population through the Rural Electrification Agency (REA) mandated to increase rural electricity access to 22% by 2022, up from the current rate of 2%.

The use of biogas in electricity generation has been

advocated for by many researchers [9-11]. Though solid biomass is the major source of energy in rural Uganda, production of biogas, an energy carrier derived from biomass, has quickly been gaining ground with the government targeting to install 100,000 bio-digesters based on cattle manure by 2017 [2]. Agriculture is the backbone of Uganda's economy and approximately 80% of the households in Uganda are involved in agricultural practices comprising of 75.4% crop growing, 57.6% livestock farming and 66.9% mixed farming [1]. A single household especially in the Western and South Western rural regions of Uganda can own as many as 800 heads of well-bred cattle since number in cattle is a sign of prestige in this part of the nation. It is evident from the stats above that as agricultural operations become gradually consolidated, the generation of wastes from these practices presents an immense opportunity for these communities to obtain feedstock for biogas production which can be used in power plant systems for electricity generation as off-grid stations, especially for such rural areas.

Okello *et al.* [12] conducted a study on the bioenergy potential of agricultural and forest residues in Uganda. As can be observed in figure 1, the authors indicated that the crop residue energy potential was about 150PJ y^{-1} and the energy potential of animal manure (human manure inclusive) amounted to about 65PJ y^{-1} . Manure from the 11.7 million heads of cattle (as of 2008) contributed an energy potential of about 45PJ y^{-1} whereas human manure contributed 2.69PJ y^{-1} , each with a 0.2m³/kg biochemical potential. The results were in conformity with the government's policy to install bio-digesters to harness this potential. However in order to utilize biogas for electricity generation, infrastructure that utilizes the produced digester gas has to be developed and implemented nationwide.

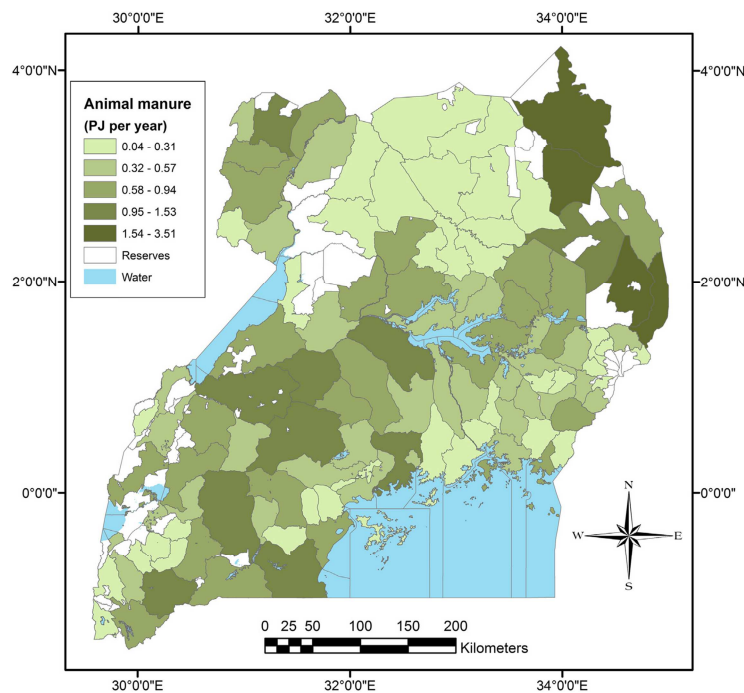


Figure 1. Animal manure energy potential distribution in Uganda. Source [12].

Apart from need to develop infrastructure, most limitations to the exploitation of biogas in power generation are attributed to the composition and nature of the biogas. Biogas is a low calorific value fuel (at about 21.5MJ/m³) compared to natural gas (36 MJ/m³). This is due to the presence of non-combustible impurities in the biogas.

In their study, Rasi et al. [13] analyzed the composition of biogas from a sewage treatment plant digester, landfill and a farm biogas plant in order to assess the potential use of biogas for bioenergy. The authors found that biogas components vary with different plants; carbon dioxide content ranges from 36% to 41%, methane from 48% to 65%, nitrogen from 1% to 17%, and oxygen is less than 1%. Sewage digester biogas contains the highest methane content; landfill biogas contains the lowest methane and the highest nitrogen contents in winter. The total volatile organic compounds (TVOCs) range from 5 to 268 mg/m³, and the farm biogas plant has the lowest TVOCs. Sulphur compounds are found in all three cases. As such biogas should be purified before injection into the natural gas grid for electricity generation [14] and to increase its calorific value by removal of acidic gases and other impurities. This process, also known as methane (CH₄) enrichment includes the separation of carbon dioxide (CO₂) from biogas [15, 16]. Purification based on CO₂ removal can be accomplished through cryogenic separation.

Membrane separation, organic physical scrubbing, chemical scrubbing, pressure swing adsorption, and high pressure water scrubbing [16]. The above techniques are discussed in detail in the SGC's report 270 [17]. However, since biogas upgrading is expensive, direct combustion is proposed for power generation when sufficient quantity of the gas is available [9].

Among several techniques implemented in biogas-based electricity generation are the gas turbine (Brayton cycle), reciprocating internal combustion engine (Otto cycle), Combined Cycle power plants, Stirling cycle engine and fuel cells [18]. The low capital cost to power ratio of gas turbines (GTs) as well as high reliability without complexity, easy commissioning and commercial operation, high flexibility and very short time for start-up and running make GTs more suitable for electricity generation [9, 19].

In particular, digester gas is suitable for small gas turbines ranging from tens of kilowatts to several megawatts because the amount of the gas produced at a single source is usually limited [20]. Unfortunately this technology has not been exploited in Uganda due to lack of experience and technological knowhow. Reference [21] reported that biogas has been variously applied for heating and/or electricity generation purposes all over the world with the authors stating that albeit biogas-based power generation is at an experimental stage in the UK, it already accounted for around 0.5% of the total output power. In the US, biogas fuels account for about 1% of power generation, while obtaining a climate-change benefit equivalent to a decrease in CO₂ emissions in the electricity sector by more than 10%.

A 1.4MW combined cycle biogas plant was simulated by [9] using MATLAB to obtain the plant's thermal design parameters. The authors gave a comprehensive report on the thermodynamic performance of the micro-power system that used GT cycle and Organic Rankine Cycle (ORC) as the top and bottoming cycles respectively. This work showed support for application in power generation systems.

Huang and Crookes [22] simulated biogas by diluting natural gas with varying fractions of CO₂ from 0% to about 40% and used it in a single cylinder spark ignition engine as fuel. The authors established that increasing the fraction of CO₂ in biogas can lower NO_x emissions and enable the compression ratio to be increased. However, the cylinder pressure is reduced, resulting in the simultaneously reductions of power and thermal efficiencies and the increase of unburned hydrocarbon emissions.

Ga et al. [23] developed a hybrid biogas-petroleum conversion kit for a station engine that consumed 1 m³ of biogas to produce 1 kWh of electricity. Compared to petroleum, the cost for the production of 1 kWh of electricity by biogas could save 0.7 US\$ and could lead to a reduction of 1 kg of CO₂ emission.

A comparative economic analysis of gas turbine-based power generation and combined heat and power systems using biogas fuel was conducted by [10]. The authors simulated a 5 MW-class gas turbine fueled with biogas and concluded that a combined cycle system could supply 22% more electricity than the gas turbine-only system with 13% shorter payback period and 34% larger total NPV than the gas turbine-only case.

In this work, simulations for biogas electricity generation as off-grid power stations in Uganda's cattle rich rural communities is conducted basing on thermodynamic concepts. This is in line with the government policy of Rural Electrification and the SDGs.

2. Materials and Methods

The methods used in this work involved data collection and analysis of the characteristics describing human population, number of heads of cattle and the need for electricity as determined by [1, 5]. Given the nature of the biogas commonly collected, two systems for power generation are used in the simulation; a gas-turbine (GT) only system and a GT-with steam turbine (ST) in the bottom cycle system were considered. Aspen HYSYS V8.8 was used for computational modeling. Since biogas is composed mainly of methane and carbon dioxide, it was assumed that trace components of accompanying other gases were negligible and the performance using biogas purity of 71% methane and 29% carbon dioxide were analyzed.

2.1. Process Simulation

Albeit some differences do exist between results obtained from process simulation and real plant process operations, modern simulation software, if effectively used, can provide

dependable information on process operation due to their comprehensive thermodynamic packages, advanced calculation techniques and vast component libraries. The case that was considered is shown in Table 1. When using HYSYS, design parameters from [9, 10] were used. The utilized system simulation and assessment was developed basing on the following assumptions:

- Energy storage and transport delay in all unit Ops are negligible thus steady state operation is applicable.
- Combustion of the fuel is 100% complete.
- From heuristics, combustion air mixture is considered ideal with composition of oxygen, nitrogen, carbon dioxide and water vapor as 0.2059, 0.7748, and 0.0003 and 0.019 respectively.
- Compressor and turbines are adiabatic

The Peng-Robinson and ASME steam thermodynamic packages were specified for the operation of the topping and bottoming cycles following the decision algorithm outlined by [24].

Table 1. Biogas Properties.

Gas Properties	Values
CH ₄ (Vol%)	71
CO ₂ (Vol%)	29
LHV (kJ/kmol)	569919.13

Table 2. Design Parameters used in the simulation model.

System part	Parameter	Design Value
Gas Turbine	Compressor Isentropic Efficiency	85%
	Pressure ratio	10
	Combustion chamber inlet temperature	335°C
	Turbine Isentropic efficiency	85
	Turbine inlet temperature	1050°C
Steam Turbine	Inlet water temperature	20°C
	Inlet water pressure	10 bar
	Steam temperature	180°C
	Steam Pressure	9.8 bar
	Turbine isentropic efficiency	85%

The procedure followed in determining the efficiency for each case is presented in equations (1)-(3)

$$\eta = \left(\frac{P_{net}}{E_{input}} \right) \times 100 \quad (1)$$

$$E_{input} = (\dot{m} \times LHV)_{biogas\ fuel} \quad (2)$$

$$P_{net} = P_{GT} + P_{ST} - P_{aux} \quad (3)$$

Where η is the overall efficiency of the system in consideration, E_{input} is the energy input of the fuel, P_{net} is the net power output of the system, P_{GT} , P_{ST} are the gas turbine and steam turbine power outputs and P_{aux} is the auxiliary power consumption in pumps and compressors.

The determination of the number of cattle required for a particular power output and digester volume was based on the equations outlined by [25] on 0.1kg of cow manure as a basis to generate power of 0.008973kWh.

$$\dot{m}_{manure} = \left(\frac{\phi}{0.008973} \right) \times 0.1 \quad (4)$$

Where \dot{m}_{manure} is the flow-rate of cow manure (kg/day) fed to the digester, ϕ is the electricity energy to be generated (kWh/day).

The rate of water to dilute the manure is calculated based on the good ratio of manure and water in biogas process 1:1 as such:

$$\dot{m}_{water} = \dot{m}_{manure} \quad (5)$$

The total feeding rate to the digester \dot{m}_{total} is the sum of the water and manure flow rates. The volumetric rate of the material feeding (m^3/day) is calculated by dividing the total feeding rate by the density of the slurry (ρ kg/ m^3) as;

$$F = \left(\frac{\dot{m}_{total}}{\rho} \right) \quad (6)$$

Thus the digester volume is determined from

$$V_{digester} = \tau(\alpha + 1)F \quad (7)$$

Where τ is the minimum retention time (10-15days) of material to make anaerobic microorganisms grow well without washout and α is a factor of safety.

Manure production was based on a typical fully grown 700kg Ankole-Watusi cattle breed which can produce as much as 50kg of manure per day [26].

2.2. System Configuration

A GT-only system and combined cycle GT-ST system are considered in this study. The GT-only system (Figure 3) was developed basing on the Brayton cycle wherein both expansion and compression occurred in same rotating movers. The system consists of three main components; the combustion chamber (G), compressor, and turbine-generator. Air is drawn in by the compressor and delivered to the combustion chamber. Biogas is fed to the combustion chamber as fuel where it is assumed to burn to completion. The produced flue gases are then passed to a turbine, where they expand and transfer energy to the turbine. The turbine propels the compressor on one hand to compress the incoming gas and the generator on the other hand to produce power. The turbine is controlled by regulating the biogas flow into the combustion chamber. In the combined cycle GT-ST system (Figure 4), the gases from the combustion chamber are fed to the gas turbine (GT) as before to generate (GT) power. The waste exhaust gases from the top cycle are captured by a heat recovery steam generator (HRSG) made of an economizer, super heater and evaporator. The HRSG heats water in a boiler to supply steam to the bottoming cycle which is based on the steam Rankine model. The steam expands in the bottom turbine to produce electricity (ST-power). Products from this bottom condensate turbine are fed into a condenser, and the water output is pressurized by a pump and sent to the HRSG.

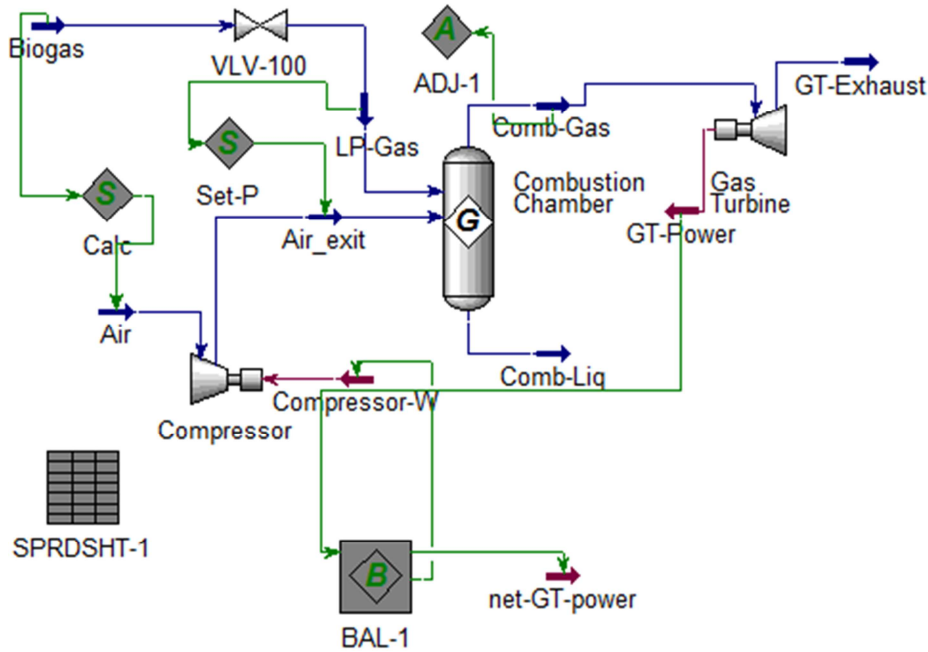


Figure 3. GT-only system configuration.

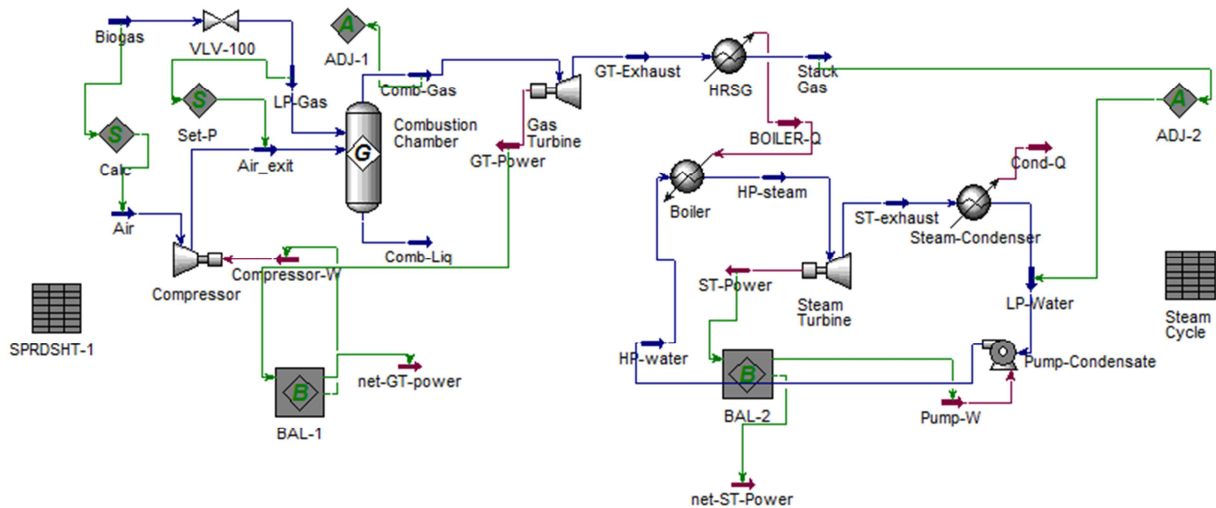


Figure 4. Combined GT-ST system configuration.

3. Results

The proposed utilization of biogas for power generation in this study is done basing on a target to generate at least 2.5MW of electricity. The simulated topping configurations were compared to the GTU-2.5P gas turbine for validation where results were in close agreement. Table 3 shows the digester need estimates to meet the minimum power generation of 2.5MW. It should be noted that the maintained cow head count is 13740, a count that can easily be met by the cattle-keeping culture of western Uganda communities. Material balance from the gas turbine alone (GT) system for a 71% methane-29% carbon dioxide are that had an efficiency of 33% is given in Table 4 showing molar and mass flow rates of biogas for each component unit. Basically the flow rates of flue and exhaust gases are the same except

their temperatures and pressures. This is because the flue gases have passed through a turbine and given their energy contents to generate electricity in the turbine (Table 4). Table 5 shows molar compositions of air, biogas, flue and exhaust gases for 29% CO₂-71% CH₄ system. The flue gas contains 5% CO₂, 13%O₂, 74%N₂, 8% H₂O and negligible amount of CH₄. Looking at these results, it can be concluded that these exhaust gases do not constitute environmental threats at all when disposed to the atmosphere.

Table 3. Digester need estimates.

Parameter	Estimate
Electricity runtime (h/day)	24
Manure loading rate (kg/day)	668,672.7
Maintained cow head count	13740
Digester volume (m ³)	23881

Table 4. Material balance for GT-alone system 71%CH₄-29%CO₂.

Parameters	Biogas	LP-Gas	Air	Compressed Air	Flue Gas	GT-Exhaust
Vapour Fraction	1	1	1	1	1	1
Temperature(°C)	25.000	18.195	25.000	335.186	1049.998	550.000
Pressure (bar)	21.013	10.010	1.013	10.010	10.010	0.852
Molar Flow (kgmol/h)	46.370	46.370	1000.000	1000.000	1046.365	1046.365
Mass Flow (kg/s)	0.311	0.311	7.958	7.958	8.269	8.269

Table 5. Molar composition of gases for GT-alone system, 71%CH₄-29%CO₂.

Air composition	Biogas	LP-Gas	Air	Compressed Air	Flue Gas	GT-Exhaust
Mole Frac (CO ₂)	0.29	0.29	0.0003	0.0003	0.044602	0.044601822
Mole Frac (O ₂)	0	0	0.2059	0.2059	0.133646	0.133645684
Mole Frac (N ₂)	0	0	0.7748	0.7748	0.74027	0.74026964
Mole Frac (CH ₄)	0.71	0.71	0	0	4.14E-34	4.14E-34
Mole Frac (H ₂ O)	0	0	0.019	0.019	0.081086	0.081085578
Mole Frac (NO)	0	0	0	0	0.000388	0.000387884

The net energy derived from it is 2.5MW which is available for use by the community. With many of such off-grid stations like this one within the cattle rearing community, the country's Rural Electrification Policy could easily be implemented in these areas. Similar occurrence happens with the combined GT-ST system for 71% CH₄ -

29% CO₂ with a better efficiency at 48% but the exhaust gas compositions remain the same Tables 6 and 7. The net energy obtained from this system is 3.55 MW which is available for use by the community. The combined GT-ST system therefore provides a better net energy output for the same purity of 71% CH₄ and 29% CO₂, Tables 6, 7, and 8.

Table 6. Material balance for combined system 71% CH₄-29% CO₂.

Parameters	HP-water	LP-Water	HP-steam	ST-exhaust	Biogas	LP-Gas	Air	Compressed Air	Flue Gas	GT-Exhaust
Vapour Fraction	0	0	1	0.803	1	1	1	1	1	1
Temperature (°C)	20.057	20.000	179.009	20.004	25.000	18.195	25.000	335.186	1049.998	550.000
Pressure (bar)	10.000	0.023	9.800	0.023	21.013	10.010	1.013	10.010	10.010	0.852
Molar Flow (kgmol/s)	298.007	298.007	298.007	298.007	46.370	46.370	1000.000	1000.000	1046.365	1046.365
Mass Flow (kg/s)	1.491	1.491	1.491	1.491	0.311	0.311	7.958	7.958	8.269	8.269

Table 7. Combined GT-ST molar composition 71% CH₄-29% CO₂.

Air composition	Biogas	Air	Compressed Air	Flue Gas	GT-Exhaust	Stack Gas
Mole Frac (CO ₂)	0.29	0.0003	0.0003	0.044602	0.044601822	0.044602
Mole Frac (O ₂)	0	0.2059	0.2059	0.133646	0.133645684	0.133646
Mole Frac (N ₂)	0	0.7748	0.7748	0.74027	0.74026964	0.74027
Mole Frac (CH ₄)	0.71	0	0	4.14E-34	4.14E-34	4.14E-34
Mole Frac (H ₂ O)	0	0.019	0.019	0.081086	0.081085578	0.081086
Mole Frac (NO)	0	0	0	0.000388	0.000387884	0.000388

Table 8. Energy flow for combined system 71% CH₄-29% CO₂.

Energy	Pump-W	ST-Power	Comp-W	GT-Power	net-GT-power	net-ST-Power
Heat Flow (kJ/s)	1.753852	1073.405	2602.47	5075.93229	2473.462646	1071.650824

The effluents that result from the production of biogas provides manure for exhausted farmlands within the community for increased crop yields.

4. Conclusions

A simulation of electricity generation from biogas was conducted for use in the Ugandan rural community using Aspen HYSYS V8.8. For a biogas composition of 71% methane and 29% carbon dioxide with the gas flow rate of 0.331 kg/s for a single gas turbine (GT) system alone, the net energy obtained from the system is 2.5 MW which is available for use by the community.

For a combined gas turbine-steam turbine (GT-ST) system,

an extra 1MW can be generated for the community to give a total net of 3.5MW. This amount of energy surpasses the need for an average community with 5000 households and the excess can be sold to the national grid to supplement deficiencies. To meet the above requirements a cattle head count of 13740 needs to be maintained, a figure that can easily be met by the cattle rich communities under consideration.

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