

Thermal analysis of a CSP-Biogas hybrid power plant

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Abstract: As the energy costs continue to rise steadily, researchers are looking for alternative sources of energy to meet the rising demand for sustainable energy. Finding an inexpensive and reliable energy generation technology is a big challenge both in developed and developing countries. Innovation and invention of new technologies, mass production and economies of scale will together enable a reduction in the cost of solar electricity to levels comparable with other electricity generating sources. Solar energy producers can increase their energy production by creating solar thermal hybrids by using concentrating solar thermal hybrids together with other energy sources like coal, biomass, oil, gas, geothermal and others. The performance of concentrating solar thermal power is limited by the availability of the sun and the design. The first solution is the hybridization of the solar power plants with fossil backup systems. For this case the fossil is used as a fuel to help meet the desired energy output of the system. Hybrid concepts are most suitable for utility application since they offer high power availability during peak and base loads operation. The hybrid model is assumed to be operated exclusively on renewable energy and net production of carbon dioxide.

Keywords: Concentrating Solar Power, Heat Transfer Fluid, Hybrid Concentrating Solar Power with Biogas Plant, Collectors

1. Introduction

The sun is a sphere of intensely hot gases of approximately 1.39×10^9 m diameter, about 1.5×10^{11} m away from the earth. Sun's rays reach the earth approximately after 8 min 20s. The sun has a black body temperature of about 5762°K . Solar energy is the energy produced directly by the sun and can be collected normally at some points on the earth using available technologies such as concentrating solar thermal power collectors and Solar photovoltaic cells. The sun creates its energy through a thermonuclear process that converts about 65000000 tonnes of hydrogen to helium each second. This process leads to the creation of heat and some electromagnetic radiation [2, 3]. The heat remains in the sun and is used for maintaining the thermonuclear reactions. The electromagnetic radiation (which includes, visible lights, infra red and ultra violet radiation) streams out into space in all directions. Only a small fraction produced reaches the earth [4].

Much of the world's required energy can be supplied directly by the solar power or biogas generated from municipal solid waste (MSW). The main advantages of

combining solar thermal power and energy from biogas recovered from MSW, over fossil fuels are that they are low-carbon renewable energy resources and have no direct effects to the environment such as emission caused by fossil fuels. In order to curb environmental pollution caused by fossil fuels, it is inevitable to strengthen efforts to the world-wide deployment of cleaner sustainable and renewable energy resources. Renewable energy sources are able to meet the needs of the present without compromising the ability of future generations to meet their own energy needs. This deployment will help compensate for the environmental impacts of fossil fuels by cutting down on carbon and green house gas emissions. Also utilization of indigenous renewable resources in a country for energy generation can pave the way for alleviation of energy poverty, employment generation, and sustainable socio-economic development. In rural Africa population density is very low and sparse. This makes the overall transmission and distribution of electricity very expensive. However these rural areas have access to renewable energy sources such as solar and MSW which can be tapped and transformed to meet their daily energy needs

and help raise the living standards. Biogas is a renewable source like the solar energy. It is obtainable from manure and plants which are readily available in the rural areas of the many African countries. The use of biogas has got some positive effects such as: 1) it saves on time and labor used for gathering firewood for cooking and helps minimizing the dangerous effects of smoke in houses, reduces deforestation and green house gases as well as reduction in the over reliance on fossil fuels such as paraffin[3,8].

There are some disadvantages of using non renewable energy sources which include:

- The traditional sources of energy such as firewood are becoming scarcer with population increase.
- The use of biomass/wood biomass is not a suitable energy source development as the trees are being chopped at a rate higher than they are being grown leading to the destruction of animal habitats around the world.
- A lot of human effort and time are being wasted in the collection of firewood which would have otherwise been spent in other useful income generation activities.
- It is reported that [1] the use of biomass and paraffin leads to eye problems, lung diseases, low birth weights, respiratory problems such as asthma, tuberculosis and heart diseases. It is further reported that about 2.6% of the total mortality rate from global diseases, (3.6% happens in the developing countries) are caused due to the use of solid fuels as they cause acute lower respiratory infections in growing children.
- Climate changes due to the introduction of the green house gases.

These issues in themselves are good motivators for introducing and embracing renewable energy sources. There is a dire need to provide efficient and affordable sources of energy which will help meet the society development goals. This paper reports on the technical aspect and energy analysis of a concentrating solar thermal power hybridized with biogas plant for electricity generation [1, 2]. The authors reports that for a solar only parabolic plant the amount of energy generated can only be used to meet the peak energy demands unlike the case of a hybridized solar with waste heat from biogas plant which can be applied for generation all day long. Solar parabolic trough has been used for this analysis since it is the most proven technology of all the CSP systems. It is also cheap and robust in nature.

2. Concentrating Solar Power (CSP) Plants

2.1. Parabolic Solar Collectors

These types of solar concentrators employ big mirrors to attain high temperatures than FPC. This is done by collecting the solar radiation from a wider area and concentrating it on a small area. They track the solar energy in one axis. This means that they can be either oriented in North or SOUTH or East to West as shown in Fig 1. The main advantage of the

east west tracking is that very little collector adjustment is made during the day and the aperture is always facing the sun at noon but the collector performance is very low in the early morning and in the evening due to the large incidence angles (cosine loss). In the North South orientation there is much cosine loss in the morning at noon and in the evening when the sun is due east or west.

In the period of one year solar energy collection is slightly higher in a horizontal North south trough field than a horizontal East- west orientation.

However during summer the north-south collects more energy than in winter unlike east-west orientation where collection is highest in winter and lowest in summer hence providing a more stable constant output [5].

The basic component of the solar field is the solar collector assembly (SCA). Each SCA is an independently tracking group of solar collectors made up of parabolic reflectors (mirrors), metal support structures, reflective tubes, and a tracking system that consists of drives, sensors and controls. The reflected energy from the SCAs energy falls on the heat collection elements (HCE). The HCE consists of glass to metal seals and metal bellows which accommodates the changing thermal expansions of the steel tubing and the glass envelope which carries the heat transfer fluid (HTF). The glass envelope tubing is a vacuum which reduces heat losses to the surroundings. The amount of solar energy collected per hour depends on the solar field availability which is the percentage of the solar field available at any given time to track the sun. Solar thermal electric power plants are designed to harvest available sunlight, either converting it to electricity immediately or storing it for future use. The ability to store collected thermal energy is partially good as it leads to a solar only power plant with firm dispatching capability [12].

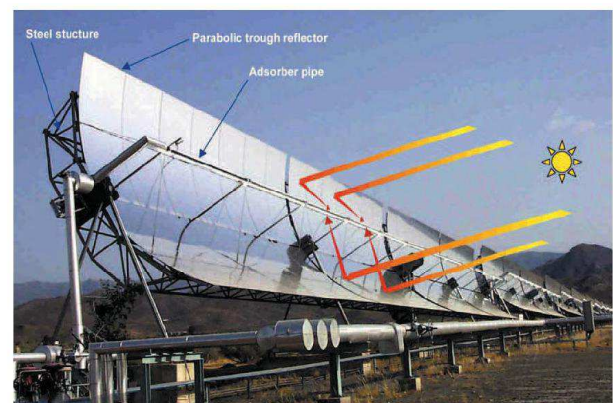


Fig. 1. Solar parabolic collector system [5]

2.2. Linear Fresnel

This employs linear array of mirrors to concentrate the sun's rays and reflect it on a fixed receiver mounted on a linear tower. Unlike PTC its shape is not parabolic hence it can accommodate large absorbers which do not have to move as depicted in Fig.2. The merit of this type of a collector is that it uses flat or elastically curved mirror reflectors which

are much cheaper compared to the parabolic troughs reflectors. One of the major difficulties of LFR as reported by [8] is that the avoidance of shading and blocking between adjacent reflectors leads to increased space between reflectors. This blocking can be reduced by increasing the height of the absorber tower but this leads to costs increase. This disadvantage has been worked on by introducing Compound Linear Fresnel Reflectors (CLFR). In this design adjacent mirrors are interleaved to avoid shading [8].

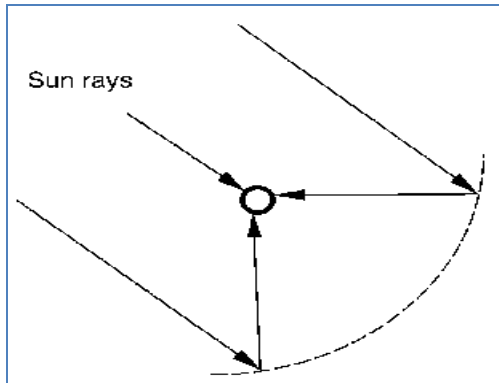


Fig. 2. Fresnel type parabolic collector [8]

2.3. Parabolic Dish

A parabolic solar dish is used for concentration of sunlight to a single point. It is also called the point focusing system [1]. Basically, the sun is concentrated on the concentrator in two axes. A reflective glass or a metalized glass reflects the incident ray to a small region called the focus. A Stirling dish is directly mounted on its thermal unit and the concentrated heat is converted to mechanical energy which runs the heat engine to produce electricity directly. There are no means of storage for this plant which makes it less popular than the parabolic trough. It requires continuous changing or adjustment of its position to maintain focus [4]. The DNI is focused on an engine system/generator that uses the Stirling thermodynamic cycle to produce electricity without producing steam. This system captures the DNI in two axes. Hence it can efficiently tap as much solar irradiation as possible. It has a high concentration, that is solar to heat concentration ration and can accumulate temperatures of up to 1450° . Its high efficiency enables it to convert 30% of the heat to electricity. Parabolic dishes can be installed in any landscape. Dish systems are air cooled and hence can be suitably located in deserts [16].

This system is mostly applicable to off-grid power generation such as islands and remote areas. Short/medium term key dish/Stirling systems are being looked forward to, for the option of hybrid dish operation, i.e. supplement combustion of natural gas integrated to the receiver system.

This is achieved in two ways:

- 1) The azimuth elevation tracking whereby the dish rotates in a plane parallel to the earth's surface and in another plane perpendicular to the elevation.
- 2) The polar tracking where the collector rotates about the axis parallel to the earth's surface [16].

Technology shortages for the parabolic dish are as below:

- a) The electricity output of a single dish is limited to small ratings.
- b) It has not been deployed in large scale.
- c) No commercial development has been done on it till date.
- d) Its cost and economic viability have not been accessed.
- e) The potential for innovations have not been done.
- f) Therefore the main disadvantages are:
- g) No large scale commercial examples,
- h) Projected cost goals of mass production still to be proven,
- i) Lower dispatch ability potential for grid integration,
- j) Hybrid model still in research and development stage.

2.4. Power Tower

The power tower technology as shown in Fig.3 converts the solar radiation from the sun into electricity for the world's electricity grids. This technology uses many mirrors called the heliostats for tracking the solar radiation on a central receiver. The sun is tracked on two axes following the azimuth and elevation angles. The technology has the advantage of transferring energy very efficiently. This is enhanced by the high radiation concentration on the central receiver unit, serving as energy input to the power conversion system

A HTF which passes on the receiver is heated and used to generate steam [17]. The heliostats are about 120m^2 in area. They are usually curved and the mirrors reflect the sun rays to a central receiver. The receiver on the tower is designed to reduce the radiation and the convectional losses. The steam in the turbine expands and produces mechanical power and electricity. The cold tank molten salts are kept at a temperature of 450°C above their melting point (240°C) [7].

The technical feasibility of the power tower was proved between 1981-1986 by the operation of the six researches or proof of concept of solar power tower plants ranging from 1-5 MWe capacities. A single 100MW plant with 12 hours of storage needs 1000 acres of desert land to supply electricity to 50,000 homes.

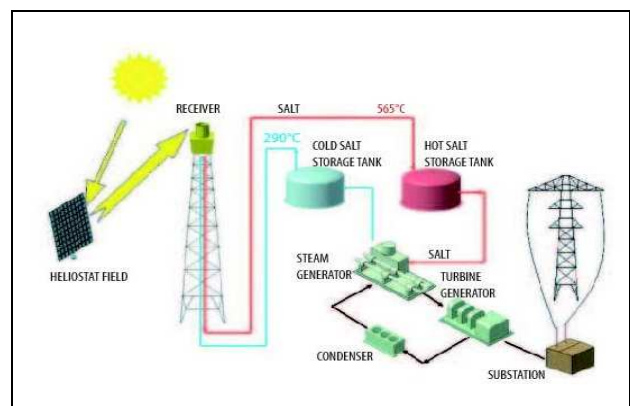


Fig. 3. Scheme of CSP plant with power tower [17]

The cited advantages of this technology are:

- Good mid-term prospects of high conversion efficiencies, operating temperatures potential beyond 1000°C.
- Hybrid operation possible.
- Better suited for dry cooling concepts than troughs and Fresnel.
- Can be used in any landscape.

The main disadvantage is that this technology has not been well commercialized.

In this simulation the authors worked on parabolic trough power plants because so far it is the most proven CSP technology. It is also robust in nature and cheap in construction as the mirrors can be made from scrap metal. Over 354MWe have been tapped using this technology in Mojave Desert in the USA.

3. Energy Analysis for Solar Parabolic Plant

The energy collected by a collector per unit area of land is given as

$$Q_{coll} = F_R I \tau_a (G - F_R U_l \Delta T) \quad (1)$$

where Q_{coll} is the collected energy in kWh per unit collector per unit time, F_R is the dimensionless heat removal, τ_a is the transmittance of the cover material of the absorber pipes, α is the shortwave absorptive constant of the cover, G is the direct normal radiation on the collector material (w/m^2), U_l is the overall heat loss coefficient of the receiver and T is the temperature of the differential between the HTF entering collector and the ambient temperature outside the collector in °K.

3.1. Collector Efficiency

The efficiency of the collector is described by equation

$$\eta = \frac{\text{useful energy}}{\text{solar energy}} \quad (2)$$

where

$$\text{Some variable} = \eta_0 - a_1 \frac{(T_m - T_a)}{a} - a_2 \frac{(T_m - T_a)^2}{a} \quad (3)$$

η_0 is the maximum efficiency at $t_m = t_a$, a_1 is the linear heat loss coefficient (w/m^2k), a_2 is the quadratic heat loss coefficient (w/m^2K^2), t_m is the average temperature of the HTF (°K) and t_a is ambient temperature (°K).

The useful energy absorbed energy by the working fluid is given as [6]

$$Q_u = M C_p (T_{out} - T_{in}) \quad (4)$$

where T_{out} and T_{in} are the outlet and inlet fluid temperatures in °K; C_p is the heat capacity of the HTF $J/(kg \cdot ^\circ K)$; m is the mass flow rate of the HTF.

Considering the losses in the atmosphere in the case of a flat plate collector putting in consideration the useful energy

gain can be expressed as:

$$Q_u = A_p F_R [S - U_l (T_{in} - T_a)] \quad (5)$$

In which F_R is the heat removal factor which can further be expressed as

$$F_R = \frac{M C_p}{U_l A_p} [1 - \exp(-F \frac{U_l A_p}{M C_p})] \quad (6)$$

in which F is collector efficiency factor and A_p is the area of the absorber surface.

The energy balance in the absorber surface can be expressed as

$$Q_u = A_p S - U_l A_p (T_p - T_a) \quad (7)$$

in which T_p is the average temperature of the absorber plate in °K and S is the radiation absorbed flux by unit area of the absorber material in W/m^2 .

The thermal efficiency of the collector is given as

$$\eta_{en} = \frac{Q_u}{I_T A_p} \quad (8)$$

Where I_T is the solar radiation per unit area of the absorber surface (W/m^2) [1, 6]

3.2. Energy Transfer between the HTF and Water

In this case we assume that the thermal fluid enters into the set of heat exchangers always at the same temperature (T_4) and exits the system at temperatures (T_1).

$$\frac{p}{m_f c_p} (x) = \frac{1}{u_s} \ln \left[\frac{(U_s - (U_s^2 - 4U_l Q_u''(x))^{0.5})(U_s + (U_s^2 - 4U_l Q_u''(x))^{0.5})}{U_s - (U_s^2 - 4U_l Q_u''(x))^{0.5}(U_s + (U_s^2 - 4U_l Q_u''(x))^{0.5})} \right] \quad (9)$$

In near future solar energy is likely to be one of the most promising sources of clean energy. This mostly applies to countries like Spain which have remarkable solar radiation throughout the year and much spare land [11].

3.3. Optical Energy Analysis

According to equation (7) above the radiation flux energy absorbed is given by

$$S = (T_\alpha) I T \quad (10)$$

where T_α is the product of the transmittance and absorptance which equals the optical efficiency of the collector η_0 .

3.4. Energy in a Collector

Energy is defined as the maximum amount of work which can be produced by or a flow of matter or energy as it comes to equilibrium with a reference environment.

$$E_{in} + E_s + E_{out} + E_1 + E_d = 0 \quad (11)$$

where, E_{in} , E_s , E_{out} , E_1 , E_d are inlet, stored, outlet, leakage and

destroyed energy respectively (J/s).

The energy inlet into the HTF is a sum of energy inlet from the HTF itself and the absorbed solar radiation rate.

$$E_{in,+} = Mc_p \left(T_{in} - T_a \ln \left(\frac{T_i}{T_a} \right) \right) + \frac{M\Delta P_{in}}{\rho} \quad (12)$$

The absorbed solar energy rate is given as

$$E_{in,Q} = \eta_0 I_r A_p \left(1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right) \quad (13)$$

The term in bracket refers to the pettela efficiency (η_p) hence the equation reduces to

$$E_{in,Q} = \eta_0 I_r A_p \left(1 - \left(\frac{T_a}{T_s} \right) \right) \quad (14)$$

At steady state conditions the amount of stored energy is null. The energy outside from the absorber pipes going to the power block includes only the energy rate of outlet fluid flow.

$$E_{out,+} = Mc_p \left(T_{out} - T_a - T_a \ln \left(\frac{T_{out}}{T_a} \right) \right) + \frac{M\Delta P_{out}}{P} \quad (15)$$

4. Thermal Analysis of a Hybrid Plant

Solar and biogas from MSW are renewable energy sources. The usage of biomass as fuel has become more attractive after the governments increased the tariffs for electricity from renewable energy sources. The costs of power from a biogas power plant depend on the quality and availability of the resource. The advantages of the hybrid energy resource would be the usage of the existing infrastructures and the existing grid and therefore the implementation costs are low. The incidence angle modifier is given by,

$$K = \cos \theta - c_1 \theta - c_2 \theta^2 \quad (16)$$

$$\Delta t = \frac{T_0 - T_i}{2} - T_a \quad (17)$$

For biogas plant alone, the energy efficiency can be expressed as,

$$\eta_{e0} = \frac{w}{E_0} \quad (18)$$

For the CSP-biogas hybrid power plant, energy efficiency can be expressed as,

$$\eta_{eh} = \frac{w + \Delta_w}{E_0 + \Delta E_s} \quad (19)$$

Δ_w =additional power generated by the saved steam and E_s is the energy of the solar radiation falling on the solar collectors.

$$\Delta E_s = I_{bin} \cdot \cos \theta \cdot A_c \left[1 - \frac{T_a}{T_s} \right] \quad (20)$$

If the energy losses are disregarded, E_s can be expressed by

$$\Delta E_s = Q \left[1 - \frac{T_a}{T_{coll}} \right] = Q \cdot \left[1 - \frac{2T_a}{(T_0 + T_i)} \right] \quad (21)$$

The efficiency of the solar collector η_{es} is given by

$$\eta_{es} = \frac{Q \cdot \left[1 - \frac{T_a}{T_0 + T_i} \right]}{I_{bn} \cdot \cos \theta \cdot A_c \cdot \left[1 - \frac{T_a}{T_s} \right]} \quad (22)$$

Calculation of the levelized cost of electricity (LEC)

$$LEC = \frac{CC \cdot A_f + O \& M + FUEL}{A} \quad (23)$$

$$A_f = \frac{q^D - (q - 1)}{q^D - 1} \quad (24)$$

where, CC= increased total capital since solar energy is introduced into the biogas power plant; q = interest rate; D=lifetime of the power plant, A_f =annuity cost; O&M= Maintenance costs; A=Annual net solar electricity generation in kWh and FUEL = other fuel costs for hybrid operation[9].

4.1. Modelling of the CSP and Biogas Plants

The authors modelled a solar concentrating solar power (CSP) plant in Lodwar Kenya. This area has an average dry bulb temperature of 29.7°C, latitude of 3.12° North and 35.62° East in longitude. The area has a direct normal radiation (DNI) of 1836.9 kWh/m² and an average wind speed of 4m/s. The area is a desert occupying a total area of about 126902 km/m².

The simulation of the hybrid plant is done in Matlab. A Matlab program file is developed based on the equations covered in Section IV to estimate the amount of power produced by each of the plant and also by the combination of the two. The required weather data inputs for the simulation of the parabolic plant is obtained Solar Advisor Model (SAM) database (www.nrel.gov/analysis/sam/) database which incorporates all weathers data of the whole world.SAM is a free software and has been extensively used in the modeling of CSP plants, PV, wind and biomass in many parts of the United States, Spain, Egypt, Morocco, Germany etc [19, 20].

5. Modeling of the Anaerobic Digester for Biogas Recovery from Municipal Solid Waste

In this study, municipal solid waste (MSW) data from

Cape Town landfill sites are used to model the biogas recovery system in Lowdar, Kenya considering similar community and economic activities in both the areas. The average daily waste tonnage values for the months of January through December, collected together in three Cape Town landfill sites, as listed in Table 1 are used in the biogas plant model.

Table 1. Average Daily Waste Tonnage per MONTH (Tonnes/day) [9]

Jan	Feb	March	April	May	June
4430	3740	3950	4200	4200	3740
July	Aug	Sep	Oct	Nov	Dec
3710	3500	3790	3800	3860	4260

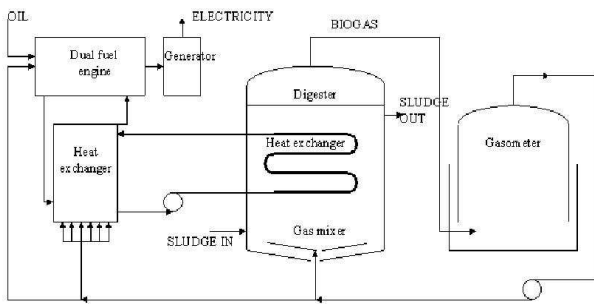


Fig. 4. Anaerobic digester model [21]

The anaerobic digester model for MSW processing is shown in Fig.4. In this model it is assumed that the biogas production is 300m³ for each tonne of MSW digested. Table 2 gives the composition of the biogas sample used in the model.

Table 2. Composition Of The Biogas Sample

Methane	55-70% by vol
Carbon dioxide	30-45%
Hydrogen Sulphide	200-4000 ppm by vol
Energy content in AD	20-25MJ/m ³

For production of methane the digestate is passed through three main stages, viz. (i) hydrolysis - where the chains of large organic polymers are broken down to monomers, (ii) autogenesis which breaks the monomers further to smaller particles and (iii) methanogenesis where these particles are further acted upon for biogas production.

The amount of electricity, thermal heat and losses due to energy conversion are estimated using Equation (25) below.

$$L_{fg} = 2 * L_0 R * (e^{-kc}) * e^{-kt} \quad (25)$$

where,

L_{fg} = amount of biogas produced from a certain amount of MSW (m³).

L₀ = assumed biogas production (ton/m³)

k = percentage rate of conversion of MSW to biogas

t = time in years.

R = annual quantity of MSW

C = number of years since the land fill closed and opened. The assumed constants for estimating the amount of heat and electricity produced in the sample used for estimating the amount of MSW is as shown in Table 3.

Table 3. Constant Values used in Equation (25)

Constant	Values used in Equation (25)
L ₀	300
R	43380
k	0.05
c	2

The retention time is assumed to be 20 days and the temperatures inside the digester between 30-35⁰C and 50-65⁰C for the mesophilic and thermophilic reactions respectively. Fig. 5 shows the flow diagram for MSW processing for electricity and heat production. The electricity generated is fed to the grid while the thermal heat is fed to the boiler of the CSP plant.

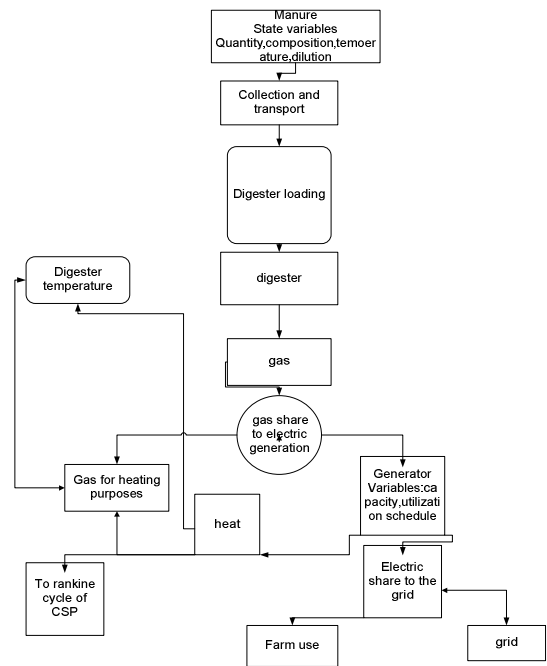


Fig. 5. Flow diagram of digestion process [22]

The amount of biogas produced from MSW and the monthly electricity and heat generated from that is calculated using Equation (25) and listed in Table 4. The losses included in Table 4 are obtained as a result of conversion of MSW to electricity and heat.

For these calculations, the following assumptions are made: (a) When biogas containing 65% methane is processed using anaerobic digestion, it yields 35% electrical power, 50% thermal heat and 15% losses. The following equivalence is also used for the amount of electricity, heat and losses in a given quantity of MSW:

- (b) 1 watt ≡ 1 joule second⁻¹; (c) 1 Wh ≡ 3600 joules (J); (d) 1 kWh ≡ 3600000 J ≡ 3.6 MJ; (e) 22 MJ ≡ 1 m³ biogas ≡ 6.1 kWh

Table 4. Energy Generation and Losses From MSW Per Month

Month	Biogas	Electricity (kWh)	Thermal heat (kWh)	Losses (kWh)
January	1.6435x10 ⁶	3.5089 x 10 ⁶	5.0128x10 ⁷	1.5038 x 10 ⁶
February	1.3875x10 ⁶	2.9624 x 10 ⁶	4.232x10 ⁷	1.2696 x 10 ⁶
March	1.4654x10 ⁶	3.1287 x 10 ⁶	4.4696x10 ⁷	1.3409 x 10 ⁶
April	1.5582x10 ⁶	3.3268 x 10 ⁶	4.7525x10 ⁷	1.4258 x 10 ⁶
May	1.5582x10 ⁶	3.3268 x 10 ⁶	4.7525x10 ⁷	1.4258 x 10 ⁶
June	1.3875x10 ⁶	2.9624 x 10 ⁶	4.232x10 ⁷	1.2696 x 10 ⁶
July	1.3764x10 ⁶	2.9386 x 10 ⁶	4.198x10 ⁷	1.2594 x 10 ⁶
August	1.2985x10 ⁶	2.7728 x 10 ⁶	3.9604x10 ⁷	1.1881 x 10 ⁶
September	1.4061x10 ⁶	3.002 x 10 ⁶	4.2886x10 ⁷	1.2866 x 10 ⁶
October	1.4098x10 ⁶	3.0099 x 10 ⁶	4.2999x10 ⁷	1.29 x 10 ⁶
November	1.4321x10 ⁶	3.0574 x 10 ⁶	4.3678x10 ⁷	1.3103 x 10 ⁶
December	1.5805x10 ⁶	3.3743 x 10 ⁶	4.8204x10 ⁷	1.4461 x 10 ⁶

6. Modeling of the Parabolic Concentrating Solar Power (CSP) Plant

Fig.6 shows the energy balance in a solar collector. Incident solar energy falling on a collector field ($I_{coll}A_{coll}$) falls on the mirror and is converted into absorbed energy (Q_{abs}). Here I_{coll} represents the DNI falling on a surface at any given time of the day and A_{coll} is the aperture area of the solar collector in m^2 . The difference between the incident and the absorbed energy ($Q_{abs} - I_{coll} \cdot A_{coll}$) gives the thermal energy losses (Q_i).

The useful absorbed energy (Q_u) is converted to thermal energy by a HTF flowing in the receiver tubes. The HTF undergoes a heat exchange where the thermal energy from the collector is used to heat some water to high enthalpy vapor which is converted into mechanical power in the power conversion block (turbine generators). The mechanical power is later converted to electrical power ready for use. In terms of land usage a CSP parabolic trough occupies an average of 20,234 m^2 per megawatt of electricity produced [23]. Such arid areas occupy 126902 km^2 as mentioned in section D above. [Where is section D? Are the arid areas in Kenya?] If 1% of this land is deployed for CSP plants 125632 km^2 of land still remains which indicates that land availability will not be a constraint in the future. [Is this in Kenya?]

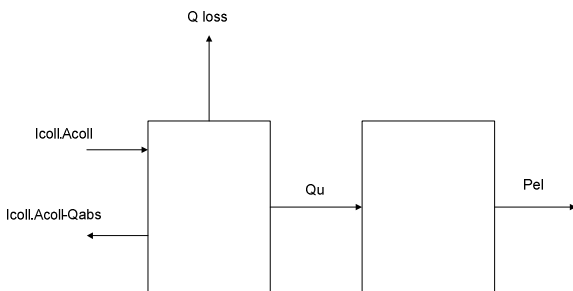


Fig. 6. Energy balance in a collector system

In case of energy transfer between the HTF and water, it is assumed that the thermal fluid enters into the set of heat exchangers always at the same temperature (T_4) and exits the system at temperatures (T_1). This plant will be located in north eastern Kenya where the available annual DNI is 1836 kWh/m^2 which compares well with CSP locations across the globe such as, Andasol 1 and 2 (50MWe each) in Spain, SEGS in Mojave desert in the USA (354MWe) and Nevada solar 1 and 2 also in USA (75MWe)[19].

DNI varies according to the time of the day and month of the year. Fig.7 shows the monthly DNI of Lodwar which is obtained from the weather database from the NREAL website.

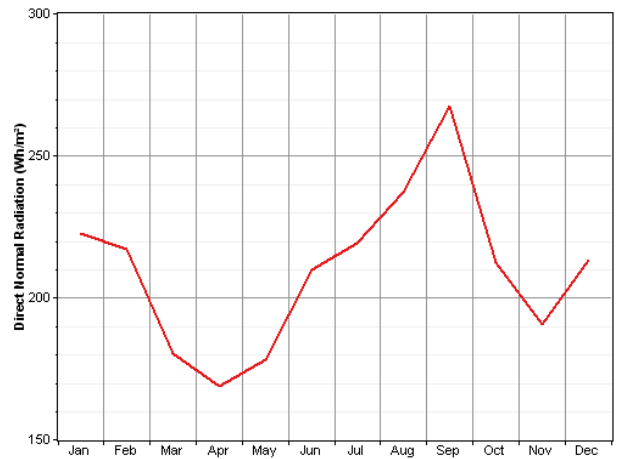


Fig. 7. Monthly DNI in Lodwar

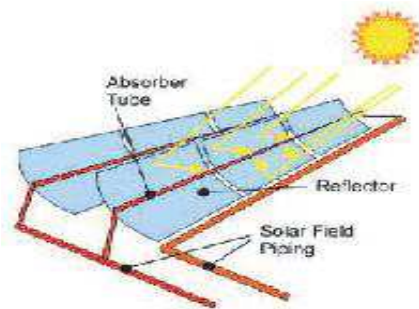


Fig. 8. Parabolic collector in a CSP plant [8]

The collector model shown in Fig.8 assumes is a physical parabolic solar collector which has the following had the following parameters as listed in Table 5.

Table 5. Physical parabolic Trough Parameters for a CSP Plant

Euro trough model	Et150
Focal length	2.1m
Absorber Diameter	7cm
Aperture width	5.8m
Collector length	95.2m
No of modules/drive	156
No of glass facets	936
No of absorber tubes	36
Mirror reflectivity	94%
Weight of steel structure	18.5kg
Aperture area	510209m ²

Table 6 shows the varying DNI in the 1st day of January in Lodwar. The collected solar irradiation per day versus the daily load profile is not matching as shown in Table 7. At night and early in the morning the DNI is zero and hence the resultant energy generation from the solar parabolic is zero. During this time of zero generation the tank is discharging the little energy stored during hours when the generation exceeded the demand. This is clearly depicted in Table 6. This is the main reason behind the biogas plant backup which ensures continuous charging of the storage tank in every hour of the day to be discharged in hours of low radiation.

Table 6. DNI in Lodwar according to Time of Day

Time of Day	DNI(kWh/m ²)	Time of day	DNI(kWh/m ²)
0100	0	1300	736
0200	0	1400	775
0300	0	1500	782
0400	0	1600	683
0500	0	1700	461
0600	0	1800	328
0700	8	1900	38
0800	246	2000	0
0900	595	2100	0
1000	605	2200	0
1100	604	2300	0
1200	586	0000	0

Table 7. Hourly Demand Versus Energy Generation From CSP

Time of Day	Energy (kWh)	Demand	Time of Day	Energy (kWh)	Demand
0100	0	4200	1300	18400	7500
0200	0	3700	1400	19373	7400
0300	0	3600	1500	19550	7300
0400	0	3600	1600	17075	7300
0500	0	3800	1700	11525	7500
0600	0	4800	1800	8200	7200
0700	200	6500	1900	950	7100
0800	6150	7400	2000	0	7300
0900	14875	7600	2100	0	7300
1000	15125	7800	2200	0	7200
1100	15100	7600	2300	0	6500

1200	14650	7800	0	3900
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7. Modeling of the Thermal Storage Unit

During night time when there is no sun stored thermal energy storage can be used to supplement the output. Solar thermal electric (STEC) can store the heat received from the sun during peak sun hours and dispatch this stored energy when additional power is required during night time and overcast periods[13].

The models assumes VP1 oil as the HTF used which is considered to be one of the most heat sensitive fluids in most CSP studies. The HTF circulates through the absorber tube where it gets heated and by the varying direct normal irradiation from the sun. The amount of heat that goes to storage depends on the heat capacity of the HTF and the temperature gradient between the charged and discharged states.

In the charging mode the HTF is heated by the sun and passed through the Rankine Cycle where it heats some water and the excess hot molten salt goes to the thermal storage tank. In the discharging mode the hot HTF flows from the hot tank to the Rankine Cycle where the heat exchange occurs and proceeds to the cold tank.

The fully discharged state of a storage system is defined by the minimum temperature acceptable at the turbine. During charging some of the heat is lost to the surroundings and only the remainder goes for storage. Contrary to this during discharging heat is lost to the environment and also taken out of the hot tank to heat some water for steam generation [5].

The thermal processes defining charging and discharging are as shown as Equations (26) and (27).

$$Q_{vp1,Charging} = Q_{storage} + Q_{loss} \quad (26)$$

$$Q_{vp1,Discharging} = Q_{storage} - Q_{loss} \quad (27)$$

The quantity of heat released or stored per hour by the HTF during a certain charging or discharging time is the time integral over the heat flow into or out of the storage system in that period of time. During charging,

$$Q_{Storage,Charging} = \int_0^t Q_{storage} = \int_0^t (Q_{vp1} - Q_{loss}) \quad (28)$$

The charging of the storage tank, according to Equation(28), only happens when the temperature between the HTF temperatures are higher than the stored energy in the tank. Charging of the storage tank is not a continuous process because of the intermittency nature of the sun.

During discharging the flow from the hot tank to the cold tank takes place. The amount dispatched depends on the electrical load on the system.

$$Q_{Storage,Discharging} = \int_0^t Q_{storage} = \int_0^t (Q_{vp1} + Q_{loss}) \quad (29)$$

The tank discharge, according to Equation (29), usually

happens during hours of low radiation, at night. The storage efficiency is dependent on the ratio between discharging and charging. Efficiency of the storage tank increases with the ambient temperature. During hours of high ambient temperature there is more charging of the storage tank than discharging. However the HTF fluid has a limited heat capacity beyond which no more heat is absorbed and the excess heat goes to waste which reduces the efficiency given by Equation(30).

$$\eta_{storage} = \frac{Q_{vp1, Disch arg ing}}{Q_{oil, Ch arg ing}} = \frac{1 - \frac{Q_{loss}}{Q_{storage}}}{1 + \frac{Q_{loss}}{Q_{storage}}} \quad (30)$$

8. Modeling of CSP-Biogas Hybrid Power Plant

The hybrid plant is modelled as shown in Fig 9. Each plant has their own power conversion units (PCU).

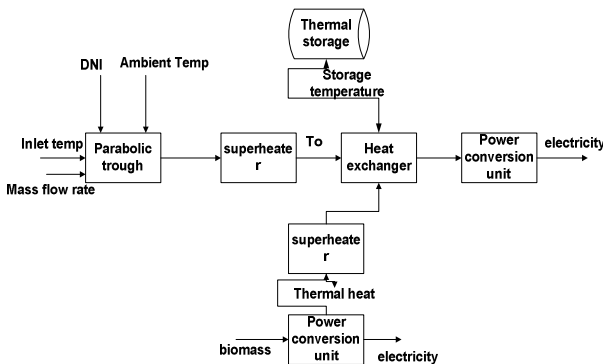


Fig. 9. Flow diagram of CSP-Biogas hybrid power plant [15]

Table 8 shows the monthly average energy production from the CSP plant from the DNI with the parameters listed in Table 5.

Table 8. Monthly DNI Versus Energy Production for CSP Plant

Month	Monthly DNI (kWh/m ²)	Monthly Energy (kWh)
January	222.46	2.3891x10 ⁷
February	216.95	2.3288x10 ⁷
March	180.55	1.9293x10 ⁷
April	168.62	1.7983x10 ⁷
May	178.35	1.9051x10 ⁷
June	209.92	2.2514x10 ⁷
July	219.44	2.3558x10 ⁷
August	237.06	2.5493x10 ⁷
September	267.42	2.8827x10 ⁷
October	212.45	2.2793x10 ⁷
November	190.68	2.0404x10 ⁷
December	213.08	2.2862x10 ⁷

The CSP part of the hybrid power plant relies on the DNI from the sun to heat up a HTF which is used to run the turbine. This generates electricity during the peak hours of the day. Biogas plant is used to augment the solar thermal plant in case of low radiation or at night. The excess heat generated from the two plants goes to storage. The two energy systems are coupled to each other via a compressed air energy storage system. Electric pumps are used for air compression to 120 bars. The solar thermal hybrid application is cheap source of energy and allows the utility companies meet their renewable energy targets, reduces emissions and also helps lower the fuel costs. During the daytime the solar parabolic power plant collects DNI which is used to run the turbine for electrical generation. Due to its intermittent nature, it is very difficult to predict when the solar irradiation will be low and when it will be adequate to generate so as match the load demand. This fluctuation in generation is the motivation the authors had, to come up with a model which combines a solar thermal parabolic power plant and a biogas plant as a hybrid power plant. The solar parabolic plant depends on the DNI available during the day while the biogas plant relies on the MSW.

The waste heat from the biogas plant is superheated and vaporized to meet the heat criteria of the heat exchanger cycle. This heat enters on the high pressure side of the heat exchanger where it is heated again by the HTF before going to the power block for turbine rotation. Fresh water from the water storage tank is first heated in the low pressure zone and afterwards reheated in the high pressure zone as shown Figure 20 below.

9. Results and Analysis

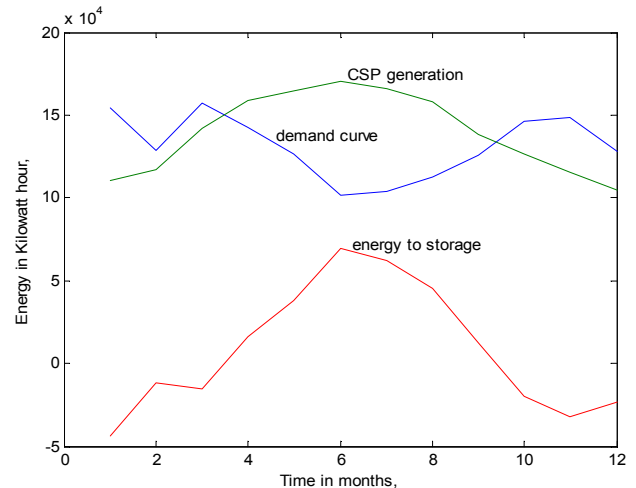


Fig. 10. Monthly energy Generation from CSP, storage and demand

It is clearly shown that at times during the day the energy generation from the CSP plant may not be enough to cater for the changing demands of electricity in the year. The excess energy generated is stored in form of heat using the HTF. However the amount of energy stored is limited by the maximum heat capacity of the storage fluid beyond which it

cannot store anymore heat. Equation (9) governs the heat exchange rate between water and the HTF. Energy is only stored when the HTF when the turbine is running at full capacity at design and only when the demand is lower than the total generated energy. A controller governs the movement of heat either to the storage system or to the turbine for electricity generation. Fig 10 shows the monthly

variation in CSP energy generation, demand and storage as per Table 7 values. The tank will only charge when energy demand is lower than the energy generated. However for a weather dependent, intermittent source of energy like the solar and wind, it might be helpful to back them up with a more certain locally available energy source such as biogas from MSW.

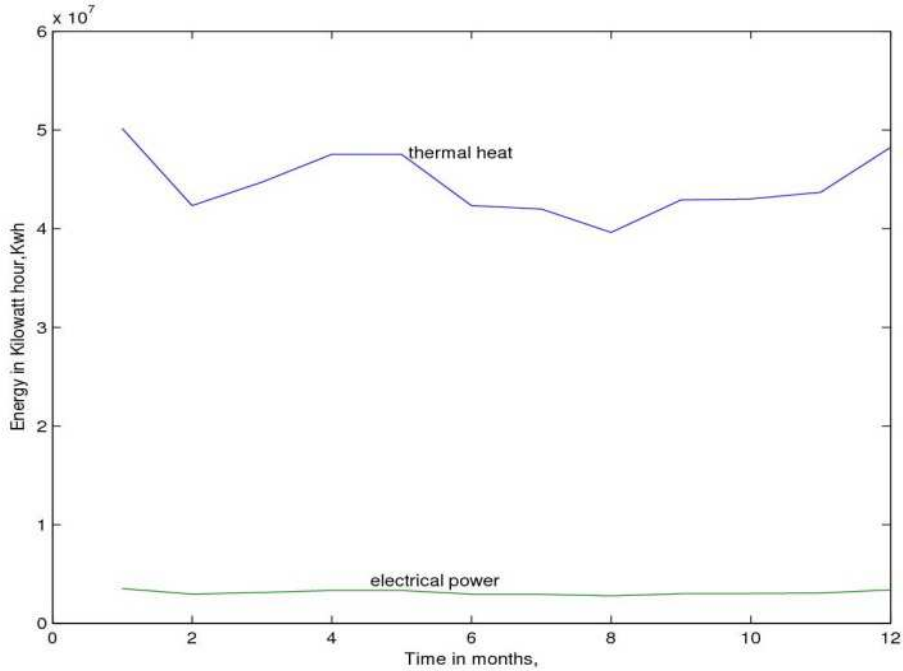


Fig. 11. Monthly electricity and heat generation in the biogas plant

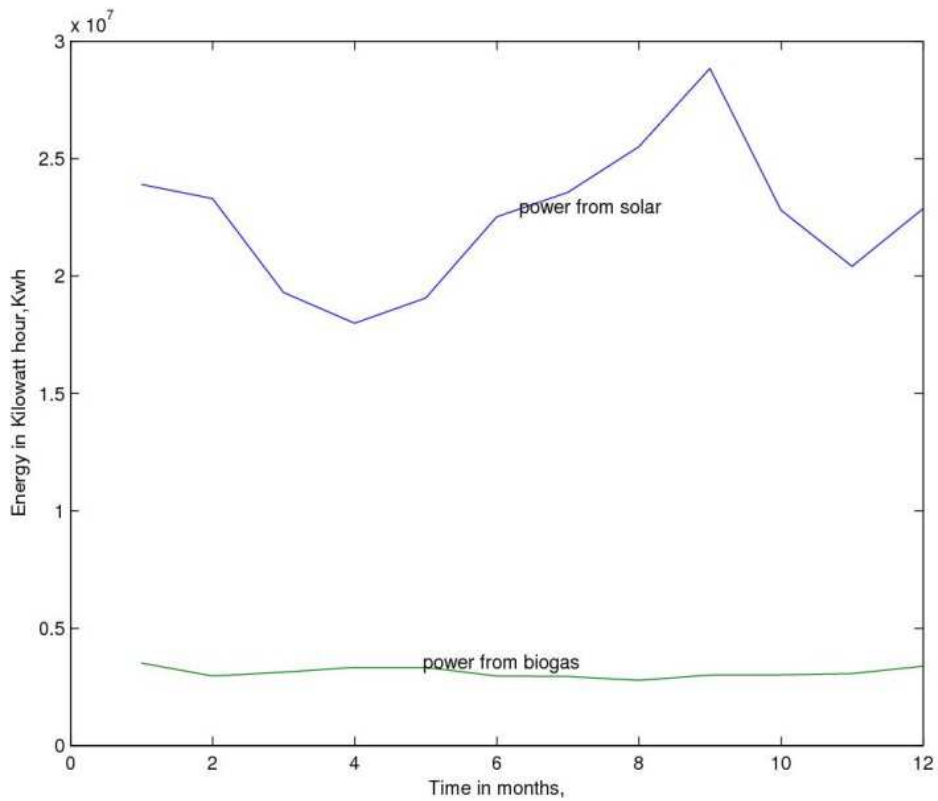


Fig. 12. A Graph of Energy (kWh) against Time (months) (Biogas waste heat & Solar)

Fig.11 shows the total thermal energy and electricity generated from the biogas plant. As depicted in Fig.11 the quantity of heat wasted is far too much than the total electricity produced. This heat is planned to be fed to the high pressure boiler of the CSP heat exchange cycle where it will be reheated and pressurized up to 120 bars and injected to the turbine. Fig.12 compares the total energy available from the combined CSP-biogas plant. The solar share is greater than the biogas share. However the solar share seems to fluctuate in some months during the year but the biogas power seems to remain almost constant. Fig.13 shows the total collected thermal heat (from both Solar and waste heat during from biogas plant) is plotted together with the equivalent electricity produced. This figure explains that the heat conversion rate (efficiency) in the CSP plant is low. This is

mainly as a result of energy loss both in storage and transit. The quantity of heat that goes to storage is now the total heat generated throughout by the biogas plus the heat generated by the solar collector. In order to match the varying electricity demand during the night and in the hours of low radiation intensity, some heat is dispatched from storage tank to add on whatever constant amount is generated by the biogas plant according to equation (31)[15]. This increases the system reliability and dispatchability. Fig 14 is used to show the importance of hybrid plant. For the same electric load demand plotted in Fig 10, but now for the hybrid plant, the load demand appears negligible. [15]

$$T^+_s = T_s + \frac{\Delta t}{Mcp_s} \cdot [Q_u(t) + Q_u B_u - L_s - (UA)s \cdot (T_a - T_s)] \quad (31)$$

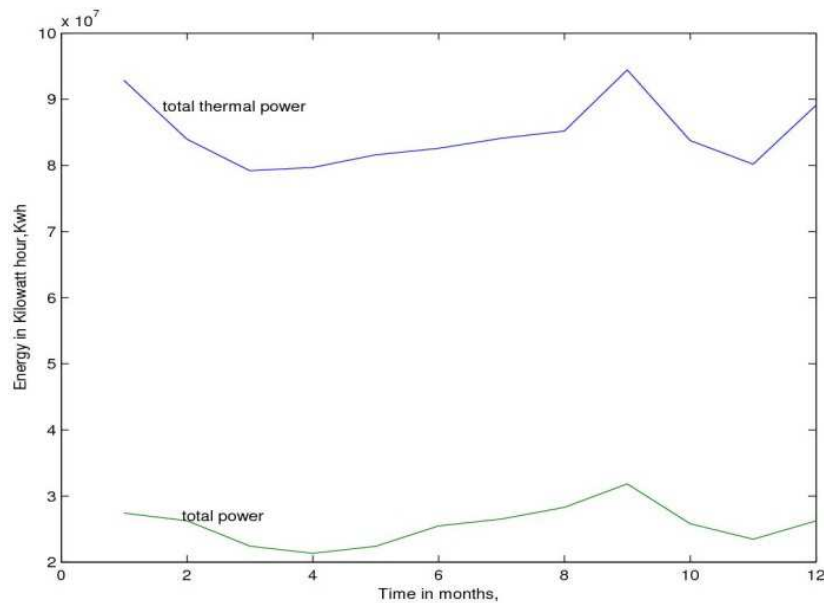


Fig. 13. A graph of Energy (Kwh) against Time in months (Solar and Biogas waste heat)

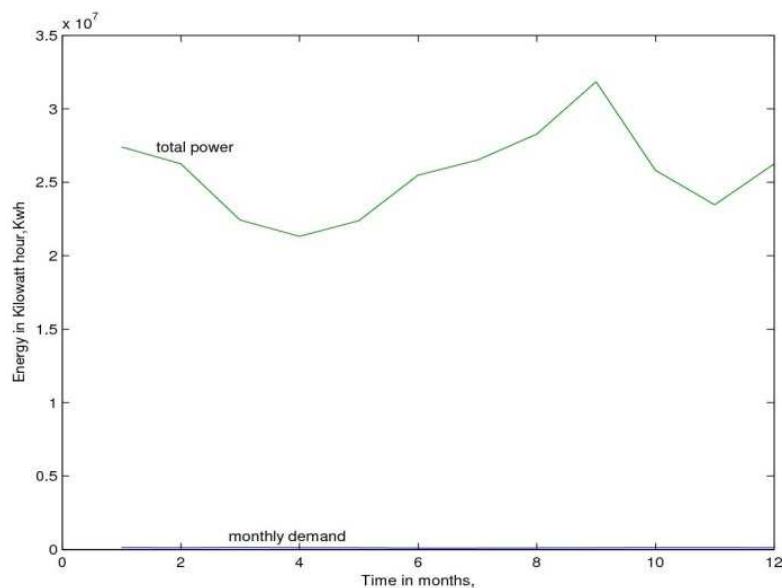


Fig. 14. A graph of Energy (Kwh) against Time in months (Hybrid)

10. Conclusion

Installation of CSP plants in North Eastern Kenya will help open this deserted area to a more economical environment. There are HVDC lines from Uganda that can be used to connect the hybrid model to the grid. The hybrid model is a viable option both for standalone applications especially for the rural African communities that are far from the main grid. For the grid connected cases the excess electricity can be solar to the grid for revenue generation. The key generators of electricity in Kenya are hydro electric which contributes to about 70% of the total installed capacity of 1200MWe. However as the population increases the needs for energy increases and majority have turn up using the woody biomass. This has lead to deforestation and therefore decreased rainfall yield per year which has resulted in water shortage for electricity production in the dams. Kenya's energy shortage can be solved by installation of renewable energy technologies since they are readily available and almost free of charge. Research and development should be done to estimate leveled cost of electricity as a result of the hybrid CSP and biogas.

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