Operation of biogas-solar-diesel hybrid renewable energy system with minimum reserved energy

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ABSTRACT

There are methods of supplying the required energy to the load while reducing the cost relatively, but do not take into account the amount of reserved energy; this is not preferred if batteries are not used to store the excess energy produced. The proposed method is a mathematical model to calculate the system size for supplying a load in an area far from the electrical grid where there are huge sources of biomass energy and high rates of solar radiation. The system includes three energy sources to generate electrical energy from solar energy, biogas in addition to a diesel generator supplying a specific load without batteries. The proposed model provides a solution that achieves an optimized system design while minimizing reserved energy taking into account minimizing the cost. The method assumes that the load is supplied first from the solar generator, when the load gets higher, the biogas generator is introduced, and the diesel generator works only if the load exceeds the capacity of the renewable sources. This scenario depends on increasing the contribution of renewable resources compared to fossil fuel.

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1. INTRODUCTION

Due to increasing demand for electric power, there is a need to develop methods of generating electricity. The use of renewable energy technologies is steadily increasing to meet the growing energy demand. People who live in remote areas prefer to use renewable energy because the installation and distribution costs of the utility grid are much higher than other areas close to the network. However, there are some disadvantages associated with renewable energy systems such as poor reliability and lean nature.

A hybrid power system is a small grid that can either be an extension of the main grid or operate independently. Several researchers have already proven that the hybrid power system is suitable especially for remote areas [1]. The importance of a hybrid renewable energy system (HRES) has been increasingly recognized to provide a sustainable and reliable power supply with low emissions and high fuel flexibility, particularly for autonomous energy systems in remote areas. Biogas is a promising renewable energy source with great potential to provide various energy services such as electricity, heating and lighting. Biogas is usually generated in anaerobic conditions from raw materials such as agricultural and animal waste. The produced biogas can be stored or converted into electricity and heat by a combined heating and generation unit, and then fed into the power distribution system and local heating network. These biomasses now account for about 14% of the world's primary energy consumption and are expected to reach 50% by 2050 [2]. According to the study published in Renewable and Sustainable Energy Reviews journal, Egypt produces annually a large amount of biomass up to 40 million tons [3]. About 52% of this biomass is eliminated by direct burning in the fields, which causes many environmental problems while it can be used to generate energy that helps in economic growth. The study revealed that Egypt has the potential to produce an enormous amount of bio-energy, especially from crop residues. There are about 12.5 million tons per year of crop residues available for use, such as sugar cane residues, cotton stalks, corn stalks and rice straw. The study found that these sources would produce a potential energy of 190 PJ per year, noting that rice straw has the highest potential for power generation in Egypt. 39 PJ was obtained from yellow corn in the Middle Egypt region and 26.5 PJ from sugar cane in Upper Egypt (PJ means peta-joules=10^{15} joules and 1 PJ $\simeq$ 280 GWH). These residues are used to produce industrial gas through the process known as biomass gasification. By heating the waste without combustion with a controlled amount of oxygen or steam at high temperatures above 700 °C, an industrial gas containing mainly carbon monoxide and hydrogen is produced. This gas can be converted to methanol, ammonia and industrial gasoline, or used directly as an alternative. This gas alone or mixed with natural gas is fed to the gas supply network. In addition to gasification, the study pointed to another source, the potential biogas in Egypt which can be obtained from the manure of 7.2 million cattle. The study estimated the amount of biogas that can be obtained daily from this source at about 0.3 million cubic meters per day [4].

Egypt is geographically located between latitudes 22 and 31.5 north, so Egypt is at the heart of the global solar belt, and is one of the richest countries in the world with solar energy. Most parts of the country, from Cairo to the far south, receive radiation exceeding 6 kWh/m^2/day near the north coast and more than 7 kWh/m^2/day maximum south of Egypt. Also, the direct sunlight is exceeding 7 kWh/m^2/day, while the number of hours of sunshine exceeds 4,000 hours per year. These rates are among the highest in the world [5]. Several researchers have presented the use of different integrated renewable energy sources (RES) as alternative power sources for various applications. Some of these studies proposed the use of off-grid solutions for rural electrification [6].

The optimum design of hybrid renewable energy systems is a hot topic and there are many literatures dedicated to this topic [7], [8]. The design problem to be formulated is related to the determination of the optimal configuration of the power system and optimal location, type and sizing of generation units installed in certain nodes, so that the system meets load requirements at minimum cost. The design of the hybrid renewable energy systems can be evaluated through its lifetime cost and emission. In calculation of the lifetime cost, changes in the monetary value due to time must also be taken into consideration. Thus, the optimal hybrid system configuration seeks a combination of generator types and sizes that result in the lowest lifetime cost and/or emission [9], [10]. Among all possible hybrid system configurations that are optimally dispatched, the configuration with the lowest "net present cost (NPC)" is declared as the "optimal configuration" or the "optimal design" [11], [12]. Many papers have studied the optimal design for different configurations of renewable energy systems with off-grid and on-grid operation [13]-[16]. HOMER program is used to determine the optimum system size based on the lowest cost of energy production [17]-[19]. Relying on the lowest cost may not be accurate throughout the operating period due to variations in prices of fuel and system components [20]-[22].

This paper aims to study providing electrical power to the selected site in Egypt through a photovoltaic (PV)/Biogas system with diesel generator as a backup source and without storage element [23]-[26]. The proposed method depends on determining the size of the system on the basis of providing the required load capacity per hour and equalizing the energy generated and the energy consumed. The study takes into account the calculation of the generated energy cost in order to achieve the lowest cost of the generation system.

2. METHOD

The proposed method depends on supplying the load with the energy required over the time period, so that the energy generated from renewable sources E_S is equal to the energy required for the load E_L.

$$E_S = \sum_{i=1}^{T} P_{PV_i} + P_{Bio_i} + P_{D_i} \qquad \text{KWh} \qquad (1)$$

Where, P_{PV_i} , P_{Bio_i} and P_{D_i} are the hourly power generating from solar, biogas and diesel respectively.

$$E_L = \sum_{i=1}^{T} P_{L_i}. \qquad \text{KWh} \qquad (2)$$

Where, P_{L_i} is the hourly load.

This technique depends on determining the area of the PV array first and then calculating the energy produced from it during the specified time period according to the values of solar radiation at the specified location. Thus, the size and the average value of the required capacity of the solar PV array can be determined.

The area of PV array A, can be calculated from the total energy required by the load at sunshine period.

$$A = \frac{\sum_{i=1}^{n} P_{L_i}}{n\,\emptyset\,\eta} \qquad \text{m}^2 \qquad (3)$$

Where, n is the total number of sunshine hours all year round, $\emptyset$ is the average value of the solar radiation (kW/m^2) and η is the efficiency of PV cell.

The hourly output power from PV array was calculated using (4).

$$P_{PV_i} = \emptyset_i * A * \eta \qquad \text{KW} \qquad (4)$$

Where, $\emptyset_i$ is the hourly solar insolation.

The rated power of PV system was calculated as the average output power from the array during the sunshine hours though the year.

$$P_{PV_{av}} = \frac{\sum_{i=1}^{n} P_{PV_i}}{n} \qquad \text{KW} \qquad (5)$$

The PV generator rated value is selected to be approximately equal to the average of the hourly load at sunshine period. The load is supplied from solar generator only in periods when the capacity of this generator is greater than or equal to the load demand P_L.

The amount of power that must be produced from the biogas generator depends on the time periods in which the load is greater than the power produced from the solar generator. The energy required from the biogas generator can be determined and then the capacity can be calculated.

If $P_{PVav} \geq P_L$, the load is supplied from PV array only and the remaining time is divided between PV, biogas and diesel generators.

The remaining time period consists of two parts; m is the total hours which correspond $P_{PVav} < P_L$ during the sunshine hours and k is the darkness hours. So, the power of biogas generator was calculated using (6).

$$P_{Bio} = \frac{\sum_{m=1}^{m} P_{L_m} + \sum_{k=1}^{k} P_{L_k}}{m+k} \qquad \text{KW} \qquad (6)$$

The periods of time in which the load exceeds the total capacity produced from the PV and biogas generators together, the diesel generator shall be responsible for feeding the load during it. Thus, the desired diesel generator capacity can be determined.

If the load demands more than the capacity of the PV and biogas generators, the diesel generator is operating to supply the load.

$$P_L > P_{PV} + P_{Bio} \qquad \text{KW} \qquad (7)$$

The rated of diesel generator, P_D is calculated from maximum load as (8):

$$P_D = \max\left|P_{L_i} - \left(P_{PV_i} + P_{Bio_i}\right)\right| \qquad \text{KW} \qquad (8)$$

where, P_{PVi} is the actual hourly output power from the PV generator at minimum difference between the load and the generated power from PV and biomass generators.

The electrical load supplying scenario is carried out according to the flowchart in the Figure 1. This technique aims to minimize the reserved energy E_{res}. The reserved energy is the difference between available generating energy from sources and actual generated energy during study period.

$$E_{res} = E_{r_{PV}} + E_{r_{Bio}} + E_{r_D} \qquad (9)$$

$$E_{r_{PV}} = \sum_{i=1}^{H_{PV}} (P_{PV_i} - P_{L_i}) \quad (10)$$

$$E_{r_{Bio}} = (P_{Bio} * H_{Bio}) - \sum_{i=1}^{H_{PL}} (P_{L_i} - P_{PV_i}) \quad (11)$$

$$E_{r_D} = P_D * H_D - \sum_{i=1}^{H_D} P_{L_i} - (P_{PV_i} + P_{Bio_i}) \quad (12)$$

Where,
H_{PV}=the number of hours at $P_{PV} > P_L$ and equal (n-m).
H_{Bi}=the number of hours the Bio system is working in a year.
H_D=the number of hours the diesel system is working in a year.

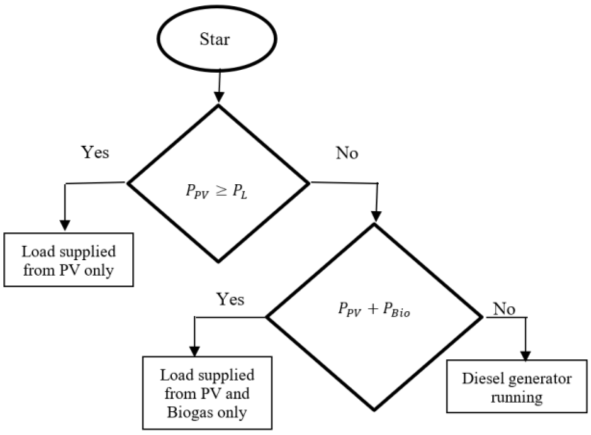

Figure 1. Flowchart of the load supplying

According this equation, the Bio system is working at total number hours H_{Bio} which equal the m+k. At this period the bio generator is working at partial load for some hours H_{PL} and full load for H_D which the diesel generator is run. Therefore, the following equation must be fulfilled.

$$m + k = H_{PL} + H_D = H_{Bio} \quad (13)$$

3. SYATEM MODEL

Hybrid energy systems mainly consist of available renewable resources at the selected area. A secondary conventional source works alongside with primary renewable sources. In this study, the ultimate objective is to design a hybrid system which meets the required demand of the selected site at a low cost with optimum efficiency using available resources. Figure 2 shows a schematic diagram with all major components, demand electricity and network of the proposed system. The proposed design system of the selected site is AC coupled. In the system design, diesel generator and biogas generator are connected to AC side. PV generator is connected with DC side of the network which is connected with a converter.

Simulation and optimization of the proposed hybrid energy system work on the basis of load demand, resources and technical specification of the components. The next sections describe the components of the entire system along with their input parameters and how the input data were processed.

3.1. Electric load

In this study, a 24 hrs load profile was assumed based on the data obtained from the site visit and typical electrical appliance for such a facility. The resulting load profile is illustrated in Figure 3. The electrical AC load consumption considered in this study is about 2426 kWh/day, the average yearly load is 101 Kw and maximum load is 405 Kw. Peak month for electricity demand is July and the months of lowest electricity demand are January and December. Figure 4 shows the hourly load for the all year.

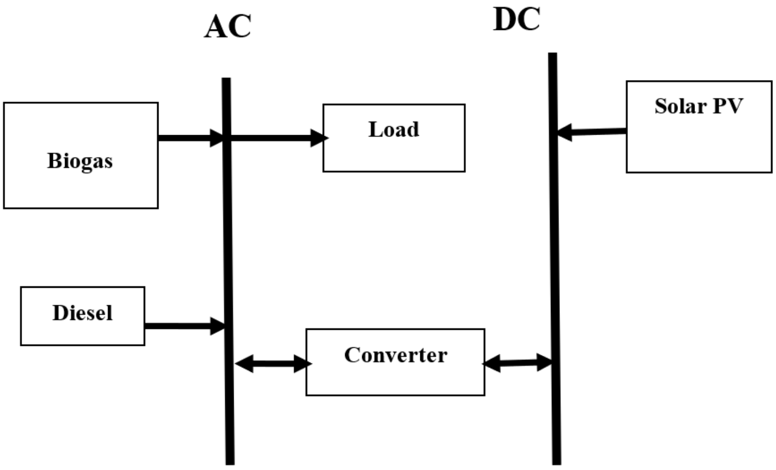

Figure 2. Schematic diagram of the hybrid system

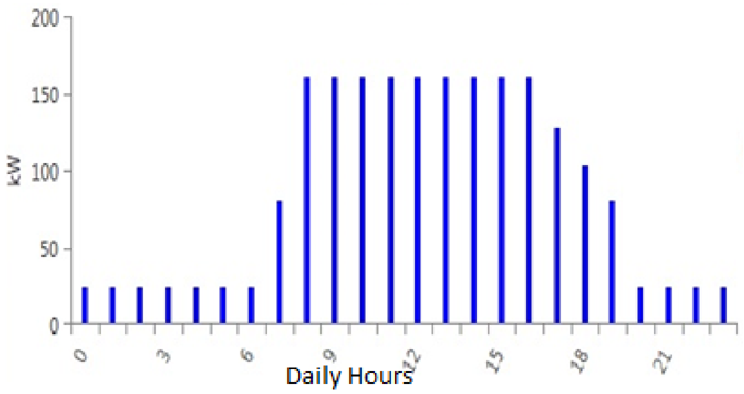

Figure 3. Daily load profile

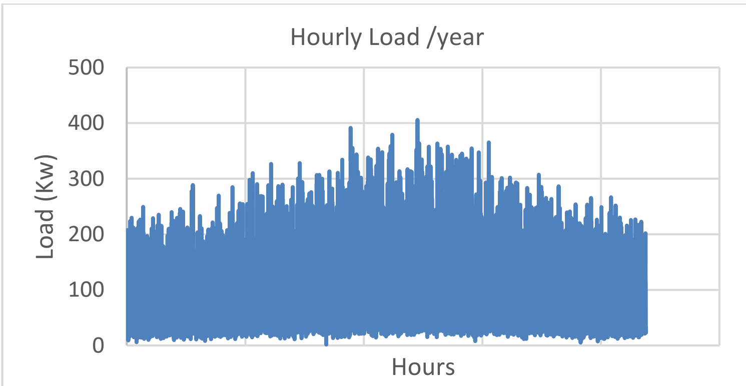

Figure 4. Yearly load profile

3.2. Solar energy

The site under study is located at latitude 22.5N and longitude 32.5E in the Governorate of Aswan, southeast Egypt. From the data obtained (NREA-Egypt, surface meteorology and solar energy ATLAS), annual average solar radiation in the selected site is about 6 kWh/m^2/day. Figure 5 illustrates the monthly average global horizontal solar radiation of the site.

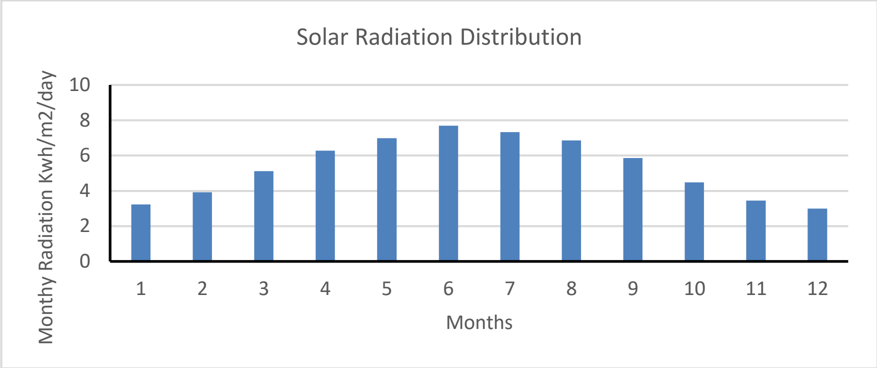

Figure 5. Average monthly solar radiation for the study site

PV generator converts the solar radiation into electricity using photovoltaic principle. In this study, the solar panel has a capital cost of LE 15000/kW including the cost of PV panels and installation. The system has a fixed orientation with a lifetime of 25 years and a de-rating factor of 80%.

3.3. Biogas generator

In this study, cows are considered as the general source of animal manure of the site. Cow dung is easily biodegradable and cow dung is considered as a renewable source for biogas production. These substances are organic in nature and their availability gives an idea of how much potential there is for biogas production. Available data from the selected site shows that cattle numbers are in the thousand with little or no figures for goat, sheep, and poultry. Theoretically, to generate 1 kW electricity, 0.73 m^3 biogas is needed. However, this study assumes an average of the waste of 1000 cows daily and if the average weight of a cow is 350 kg. This gives an available biomass of 10 ton/day while the amount of biogas yield per unit dry mass of whole input (0.2 to 0.4 m^3/kg) of fresh material.

3.4. Diesel generator

In the system design, diesel generator is used because the PV and the biogas generators are not sufficient for the load. To supply the specified load by PV and biogas only, the size of the system will increase, resulting in increased the capital cost. In addition to the limited production of biogas because the available quantity of cow dung in the selected site is limited.

4. ECONOMIC OPTIMIZATION

The cost of energy (COE) is a measure of costs that attempts to compare different methods of electricity generation on a comparable basis. It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime [27], [28]. The proposed method to calculate the COE for the hybrid system is given in [29]. In this paper, the COE is given by (14), which the lifetime of the hybrid system in years. The cost is calculated for one year by converting the present cost into an annual cost using (16).

$$COE = \frac{AC}{E_{PV}+E_F} \quad \$/kWh \tag{14}$$

$$AC = AIC + O + F \quad \$ \tag{15}$$

$$AIC = IC\frac{i\,(1+i)^T}{(1+i)^T-1} \tag{16}$$

$$IC = IC_{PV} + IC_{Bio} + IC_D \quad \$ \tag{17}$$

$$O = O_{PV} + O_{Bio} + O_D + M \quad \$ \tag{18}$$

$$F = F_{Bio} * H_{Bio} * C_{Bio} + F_D * H_D * C_D \quad \$ \tag{19}$$

$$E_{PV} = P_{PV_{av}} * n \quad KWh \quad (20)$$

$$E_F = P_{Bio} * H_{Bio} + P_D * H_D \quad KWh \quad (21)$$

Where,
AIC=the annual installation cost.
C_{Bio}=the cost of cubic meter of biogas.
C_D=the cost of liter of diesel fuel.
COE=the Cost of Energy.
E_{PV}=the total energy output from PV generator.
E_F=the total energy output from biogas and diesel generators.
F=the annual fuel cost.
F_D=the fuel consumption of diesel lit/hr.
F_{Bio}=the fuel consumption of biogas m^3/hr.
IC= he total installation cost.
i=the interest rate.
O=the total operation and maintenance cost.
T=the lifetime of the hybrid system in years.

5. RESULTS AND DISCUSSIONS

In this study, the proposed system combines PV, biogas generators and diesel generator (conventional) through hybrid energy system (HES) to create a sustainable system regarding local resources. To meet the estimated demand of the locality, the method is proposed to determine the size of system components and estimate the economic parameters. The proposed method is a simple mathematical model for determining the optimal system size for supplying autonomous load. For the specific load, and by applying the proposed model in the specified geographical area, the optimum system size was found for the specified load as PV generator is 160 Kw, bio generator is 60 Kw and diesel generator is 230 Kw. The output energy from each component and the load demand energy are shown in Figure 6. From the figure it is shown that the total energy produced is greater than the energy required for the load. It is also evident that reliance is first on utilizing all the energy produced from PV system, then from biogas energy, and finally the diesel generator works to cover the energy shortage in the event that the load capacity is greater than the energy produced from renewable sources.

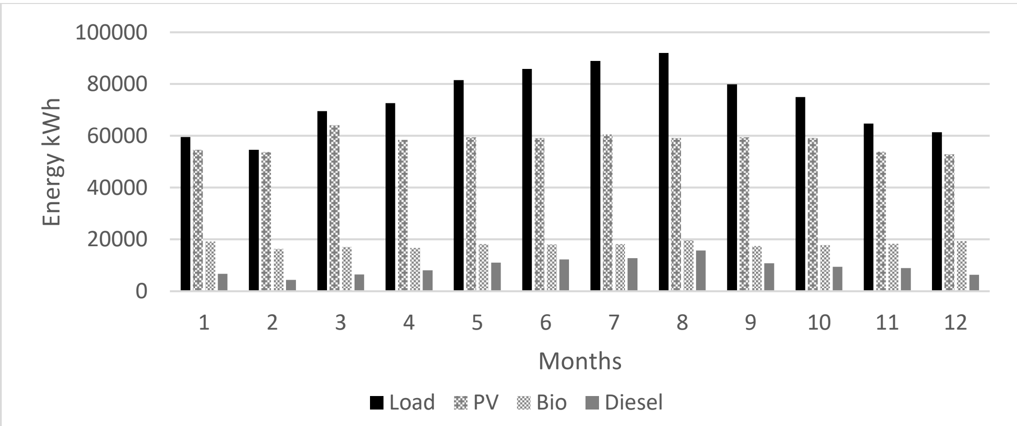

Figure 6. Energy distribution for the load and the sources

The proposed system does not contain batteries. Therefore, in order to ensure the provision of the energy required for the load, all the proposed hybrid system configurations shall produce an excess amount of energy over the required load capacity. The optimum system is chosen according to the lowest reserved energy, taking into account the reduction of the cost. The reserved energy is the difference between the total capacity of the energy produced from the sources and the actual energy produced. The reserved energy is illustrated in Figure 7. The total calculated reserved energy is 599 MWh/year.

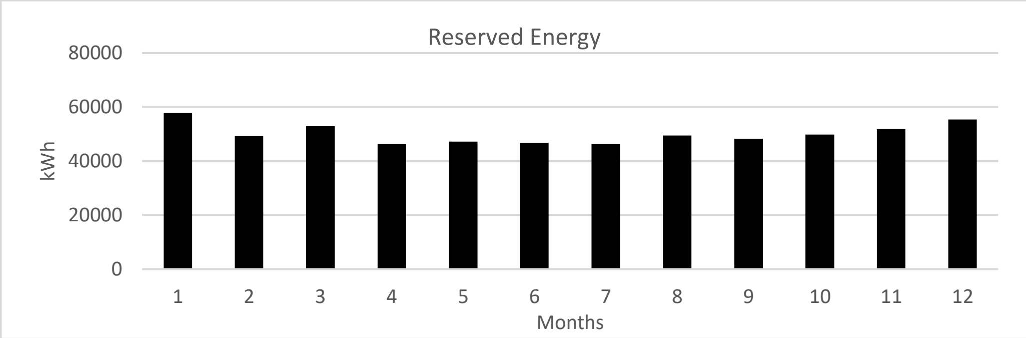

Figure 7. Reserved energy distribution

In this study, there are three energy values that determine the performance of the system. The first value is the load demand energy, the second is the actual produced energy and the third value is the capacity of the sources. Figure 8 shows the percentage of total produced energy is 54% and the load energy is 46% then the excess energy is the difference between them and equal 8%. The proposed method aims to minimize this ratio while providing the required power for the load every hour during the study period. By using HOMER program, the excess energy was not less than 200 Mwh/year (20%).

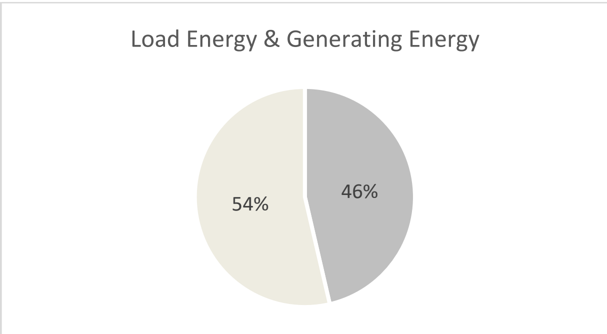

Figure 8. The percentage of total produced energy and load energy

It is clear from the results that biogas energy contributes significantly to the amount of energy produced followed by PV energy, due to the availability of biogas sources and the high rates of solar radiation in the specified area. Also, the high cost of diesel is due to the remote location of the load. Due to the low capacity of the biogas generator compared to the capacity of the PV generator and the diesel generator according to the proposed calculation method, the number of operating hours for the biogas generator becomes greater than the PV generator. Since the proposed calculation method is based on supplying the load from renewable sources first, the number of operating hours of the diesel generator will be the least. The hybrid system used achieves optimum utilization of all system elements, as each component produces the required amount of energy within an appropriate number of operating hours. It has been found that the PV produces the energy within 4378 hours, while the energy from biogas is produced within 6525 hours and the diesel generator works for an estimated number of 1934 hours. The operating hours of PV generator are divided into two parts, in the first part, the production is sufficient for the load, (H_{PV}=2235) hours. For the second part, the production is not sufficient for the load, (m=2143) hours and we need to operate the biogas generator. The total hours of biogas operating equal (m+k) and k is 4382 hours. This period is divided into H_{PL}=4591 hours and H_D=1934 hours. Note that, the total working hours of bio generators (m+k) equal 6525 and H_{PL}+H_D=6525 hours. The distribution of operating hours is illustrated in Figure 9. The proposed method is based on supplying the load from the solar energy generator throughout the hours of sunshine, and then completing the load requirements from the power of the biogas and the diesel generator, respectively. This method increases the renewable fraction which describe the ratio of renewable energy production and load demand energy.

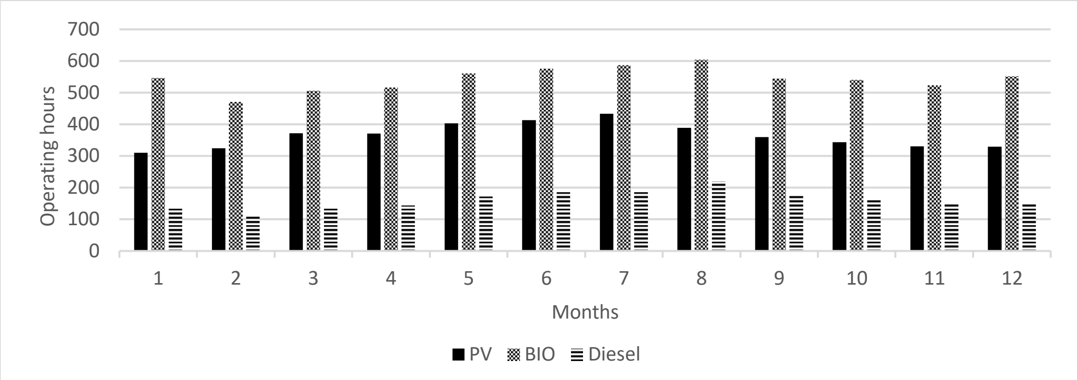

Figure 9. Operating hours distribution for the energy sources

The different hybrid systems have different renewable fraction (RF) and the COE is different for each system. The results of the simulation program indicate that the lowest COE obtained is 0.12 $/kWh achieved at 0.87 renewable fraction produced from hybrid system consists of PV, biogas and diesel generators. The low cost is noted with the increase in dependence on renewable energy sources, and this is due, as previously, to the presence of the load in a remote area with the availability of biomass sources and the high solar radiation.

The proposed method is applied for other two configuration systems. The first system has PV capacity reduction by 10 kW and the second system has PV capacity increased by 10 kW. The first system has a rated diesel generator 240 Kw while the second 230 Kw. The bio generator stayed on the same capacity 60kW.The comparison results for three systems are illustrated in the Table 1.

Table 1. Results of the proposed method for different system combinations

System Configuration	m	k	H_{pL}	H_D	H_{Bio}	Eres Mwh/year	RF	COE $/kWh
PV=160, Bio=60, Diesel=230	2143	4382	4591	1934	6525	599	0.87	0.12
PV=150, Bio=60, Diesel=240	2316	4382	4654	2024	6678	604	0.866	0.126
PV=170, Bio=60, Diesel=230	1949	4382	4497	1834	6331	614	0.878	0.122

The diesel generator works for the entire period with part of its capacity, as well as the biogas generator works for a number of hours, also with a portion of its capacity. The fuel consumption of these generators increases when they are operating at part of their capacity due to the decrease in efficiency. When calculating the cost, the increase in fuel consumption was taken into account when the generators operate at a portion of their capacity, and this naturally increases the cost of production of kWh.

6. CONCLUSION

The proposed method has been presented to size the power system to supply an autonomous load. This method was adopted to provide the energy required for the load throughout the operating period, while reducing the reserved energy and reducing the cost of energy throughout the operation period. According to the load values and location, it was found that increasing the contribution of renewable energy leads to a decrease in the cost of energy production. The COE 0.12 $/kWh and renewable fraction 0.87 are achieved for the optimal system with minimum value of reserved energy. The number of operating hours of the biogas generator is the most, followed by the operating hours of the PV generator and then the diesel generator, while the total energy produced from PV generator is the most. In all cases, the number of operating hours of the diesel generator and the power produced from it are the lowest among the three sources. The results were compared with other methods, and it was found that the proposed method gives adequate results with a reduction in the amount of reserved energy. The total reserved energy was found to be 599 MWh/year. The proposed method produced a size for a power system that gives the least reserved energy with the lowest cost compared to other sizes of systems that can supply the same load. While studying the economics of the different systems, the current price of the Egyptian pound was taken into consideration and the cost was calculated in US dollars.

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