Cost Benefit Analysis of Self-Optimized Hybrid Solar-Wind-Hydro Electrical Energy Supply as compared with HOMER Optimization

Amevi Acakpovi
Accra Polytechnic
P.O BOX: GP561

Essel Ben Hagan
Accra Institute of Technology
P.O. BOX: AN-19782

Mathias Bennet Michael
Accra Polytechnic
P.O BOX: GP561

ABSTRACT
The purpose of this paper is to evaluate the cost benefit of a self-optimized solar-wind-hydro hybrid energy supply and to compare the outcome with a similar optimization done with the HOMER software. In reality HOMER optimization software has long been used for hybrid system optimization and many do consider it as the reference software for any optimization related to hybrid energy systems. However, due to some few lack of flexibility in the setting-up of constraints and also the ignorance of the true optimization approaches used by the HOMER, it has become necessary to develop self-optimized algorithms based on rigorous mathematical models. One of these self-optimized models, developed in a previous study, was presented in this paper and was tested with data collected at Accra, Ghana. Results show that the cost of electricity proposed by the HOMER, 0.307$/kWh, is slightly lower than the one obtained through the self-optimized method, 0.442$/kWh. Moreover looking at the dynamism of selecting different sources to achieve the optimization at a lower rate for the user, more credit is given to the developed method than the HOMER because the self-optimization method gives more priority to the wind turbine than the solar plant due to the higher electricity cost of solar (0.64$/kWh). It was however observed that the HOMER software does the opposite in terms of priority. Moreover the probability of unmet load is lower with the self-optimized method than the HOMER result which consists of a big contribution because it is a major quality measure for hybrid systems to always satisfy the load request.

General Terms
Hybrid energy, Cost optimization, Matlab programming, Homer Optimization

Keywords
Solar Energy, Wind Energy, Hydro Energy, Cost optimization, Matlab Simulation, HOMER optimization

1. INTRODUCTION
HOMER is known to be the global standard for microgrid optimization. According to [1], HOMER is a computer model that simplifies the task of designing hybrid renewable microgrids, whether remote or attached to a larger grid. HOMER's optimization and sensitivity analysis algorithms help to evaluate the economic and technical feasibility of a large number of technology options and to account for variations in technology costs and energy resource availability. However, HOMER software does not give a clear account on the analytical approach of the optimization technique adopted to solve most microgrid optimization problems. In addition, HOMER does not provide flexibility to a user to set his optimization problem with some special constraints like the case where individual prices of different sources of electricity are already fixed on market. In a nutshell, despite its name and global influence on hybrid renewable energy market, HOMER does not satisfy all needs for hybrid renewable microgrid optimization and this is the reason why many other scientists investigated several other approaches often based on rigorous mathematical methods.

Existing optimization of solar, wind, hydro, and diesel generator were handled with the approach of particle swarm optimizations. In this regard, Amer (2013), [2] proposed an optimization of renewable hybrid energy system for cost reduction using Particle Swarm Optimization (PSO) approach. Bansal & al. (2010), [3] used a Meta Particle Swarm Optimization technique to perform the cost optimization of a hybrid wind, solar and storage battery. In addition, Ram et al. (2013), [4], used metaheuristic particle swarm optimization approach to develop the optimal design of a stand-alone hybrid power generation plant comprising of wind turbine generators, PV panels and storage batteries connected to a diesel generator for additional needs. Furthermore, Trazouei (2013), [5] also used the imperialist competitive algorithm, particle swarm optimization and ant colony optimization to determine the optimum configuration of a hybrid wind, solar and diesel energy supply. More advanced optimization approaches were proposed by Sharma & al. (2014), [6] who developed a new methodology, hybrid GAPSO (HGAPSO), a combination of GA and PSO approaches to achieve cost optimization of an off-grid hybrid energy system (HES). GA is known to suffer from low speed convergence while PSO suffers premature convergence but the new algorithm proposed by [6] has tremendously improved on the speed and brought about a global convergence. Idoumghar & al. (2011), [7], presents a novel hybrid evolutionary algorithm that combines Particle Swarm Optimization (PSO) and Simulated Annealing (SA) algorithms that basically work on the premature defect of simple PSO.

On the other hand, Ekren et al. (2009), [8] used a commercial simulation software named ARENA 12.0 to perform the simulation of PV/wind integrated hybrid energy system with battery storage, under various loads. Wei (2008), [9] further used the approach of genetic algorithm to determine the optimum sizing of a PV-Wind hybrid system. Also, Ashok (2007), [10] designed an optimized model to add wind, solar and micro-hydro hybrid energy. The algorithm senses wind velocity, solar radiation and load requirement to actually control the hybrid system. Power generated by each sources have been modelled and fed to an analytical model. Results help in sizing and choosing the best components to provide the optimal power.

It is extremely important to realize that most of these modern ways of optimizing hybrid energy system are targeting the sizing of system which relates to capital cost but do not necessarily provide a comprehensive analysis on levelized cost of electricity which implies the cost of electricity for the hybrid system. There is no clear evidence on how all these modern techniques have improved upon the reduction of electricity fees which should be the main target of hybrid energy supply. HOMER software actually fills this gap by providing a comprehensive analysis based on cost but also fail to bring clarity on the rigorous optimization method adopted. Moreover, there is no clear basis to evaluate the cost of hybrid system provided by HOMER because of the unavailability of other tools to compare with.

The first part of this paper presents the available resources and load requirement for the site that will be used for testing. This is followed by a deep review of a solution proposed to a cost optimization problem of solar-wind-hydro hybrid energy system developed by Acakpovi et al. (2015), [11]. The paper, further implements a solution to the same problem with the Homer software and finally compare the results obtained from both solutions to the optimization problems.

2. METHODOLOGY

2.1 Available Resources and Energy Demand

Secondary data were collected at Accra-Ghana using the RETSCREEN Plus software. The location of the site used is latitude 5.6 North, Longitude -0.2 East and elevation 68m. Solar radiation and wind profile were also collected from the RETSCREEN Plus software for the year 2013. The profile of available wind speed at the selected location as well as solar radiation profile are shown in table 1 and respectively plotted in figure 1 and figure 2.

Table 1: Wind Speed and Solar Radiation Profile of Accra-Ghana (2013)

Month	Solar Radiation	Wind Speed
Jan	4.10	2.6
Feb	4.59	2.6
March	5.21	2.6
April	5.08	2.6
May	5.02	2.1
June	3.97	2.1
July	3.70	4.6
Aug	3.84	5.1
Sept	4.59	5.1
Oct	5.19	2.6
Nov	4.79	4.6
Dec	3.86	2.1

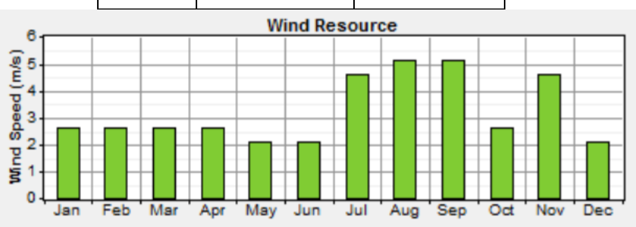


Fig 1. Wind Speed Profile for Accra-Ghana (2013)

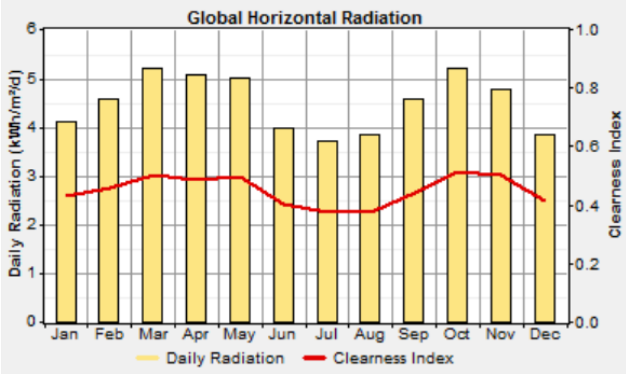


Fig 2. Solar Radiation Profile for Accra-Ghana (2013)

Besides, for the water resources, an average water flow of 100l/s was considered with some random variability for different month. The profile is shown in figure 3.

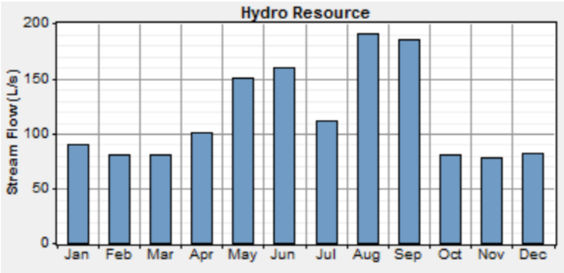


Fig 3. Average Water Flow per month

On the other hand, the load profile is created on a hypothetical basis. An average load of 6 kW appears throughout a day with some random variability accounting for an average of 250 Wh consumption per day. Figure 4 depicts the load profile

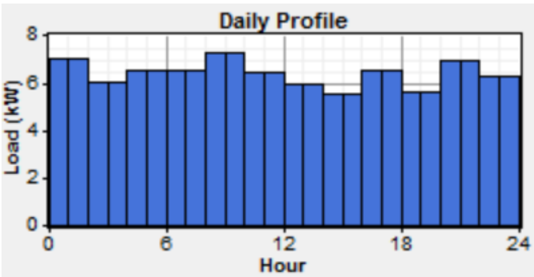


Fig 4. Hourly Load Profile

2.2 Review of Optimization Problem and its Proposed Solution

2.2.1 Adopted Models of Individual Sources

The paragraph below presents a brief model of power generated by the following individual sources: solar, wind, and mini-hydro generators.

- Analytical model of Solar Energy Generation

According to previous works done by Acakpovi et al. (2013), [12], Villalva (2010), [13], Ramos-Paja (2010), [14], and Tsai (2008), [15], the model of power generated by a PV module can be given by the formula below:

$$P(t) = n_r[1 - \beta(T_c - T_{cref})] \cdot A \cdot G(t) \qquad (1)$$

Where n_r is the reference module efficiency, T_{cref} is reference cell temperature in degree Celsius, A (m^2) is the PV generator area and G(t) is the solar irradiation in tilted module plane

(Wh/m^2), β is the temperature coefficient, Tc is the cell effective temperature.

- Analytical model of Wind Energy Generation

The model of wind power can be derived from works done by Khajuria (2012), [16], Abbas (2010), [17], and Acakpovi (2014), [18] as follow:

$$P_m(t) = \frac{1}{2}\rho A C_p V_w^3(t) \quad (2)$$

Where:

- C_p is the coefficient of performance also called power coefficient
- A is the swept area by the turbine' blades (m^2)
- ρ is the air density (kg/m^3)
- V_w is the wind speed (m/s)

- Analytical model of Mini-hydro generators

The general formula for the determination of hydraulic power is shown by Fuchs et al. (2011), [19], Hernandez et al. (2012), [20],Naghizadeh et al. (2012), [21] as follow:

$$P_m = \eta_t \rho g H Q(t) \quad (3)$$

Where: P_m is the mechanical power produced at the turbine shaft (Watts), ρ is the density of water (1000 kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), Q is the water flow rate passing through the turbine (m^3/s), H is the effective pressure head of water across the turbine (m) and η_t is the efficiency of the turbine.

2.2.2 Assumptions

With reference to Acakpovi & al. (2015), [11] the following assumptions are made:

- Each module is considered independent at the construction level and therefore their various cost of electricity will be estimated separately.
- There exist numbers N_s, N_w and N_h representing respectively the total number of solar plant, wind power plant and mini-hydro power plant respectively in existence.

2.2.3 Optimization Problem Formulation

Considering the unit costs of electricity C_{us}, C_{uw}, C_{uh}, generated respectively by the solar, wind and hydropower plants, the cost of electricity generated by the hybrid energy system over a period of time T was expressed in the previous paper, [11], as follows:

$$CE = a_s C_{us} \eta A G T + a_w C_{uw} \frac{1}{2}\rho A C_p V_w^3 T + a_h C_{uh} \rho g H Q T$$

The unit cost of electricity is further evaluated based on equation 5 below:

$$C_u = \frac{C_c \cdot CRF + C_o}{E_T} \quad (5)$$

Where C_c represents the capital cost of investment, CRF is the capital recovery factor, C_o is the operation and maintenance cost and E_T is the total energy generated over a year.

The objective function is given as follow (4)

Minimize CE subjected to the following constraints:

1. The power generated by the hybrid system should meet the demand at any given time as expressed below:

$$a_s \cdot P_S(t) + a_w \cdot P_W(t) + a_h \cdot P_H(t) \geq P_d(t) \quad (6)$$

2. The total power generated should be within range of minimum and maximum power that can be generated (7)

$$P_{min} \leq a_s \cdot P_S(t) + a_w \cdot P_W(t) + a_h \cdot P_H(t) \leq P_{max}$$

3. Variables should also stay between bounds as follow

$$\begin{cases} 0 \leq a_s \leq N_s \\ 0 \leq a_w \leq N_w \\ 0 \leq a_h \leq N_h \\ 0 \leq a_s, a_w, a_h \\ G_{min} \leq G \leq G_{max} \\ V_{wmin} \leq V_w \leq V_{wmax} \\ Q_{min} \leq Q \leq Q_{max} \end{cases} \quad (8)$$

With the assumption that the irradiation G, the wind velocity V_w and the water flow Q are all constant during the period T, the problem was considered as a linear optimization function subjected to linear inequalities constraints.

2.2.4 Proposed Solution

The solution to the above optimization problem is constructed around the linprog function of Matlab and can be described by the following algorithm.

1. Initialize an index variable to N that will serve for iteration.
2. Get the input load data, wind velocity, solar irradiation and hydro data (water flow and total head) as well as necessary data to evaluate the unit cost of electricity per individual sources
3. Calculate the power generated by individual sources of renewable energy generator using the models described above
4. Create decision variables for indexing
5. Define lower and upper bounds for all variables
6. Define linear equality and linear inequality constraints
7. Define the objective function
8. Solving the linear optimization problem with the function linprog of Matlab
9. Save result
10. Increase the index N by 1
11. If index N is less than or equal to 12 (for the twelve months in a year), repeat processes from 2 to 10
12. Display result
13. Stop.

2.3 Implementation with HOMER Software

The general scheme of the proposed hybrid system is shown in figure 5. Also, table 2 summarizes the main cost configurations of the system implemented in the HOMER software.

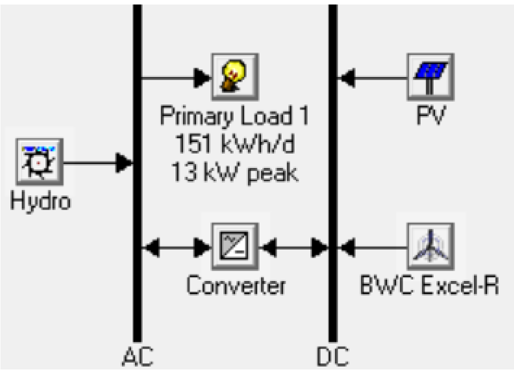


Fig 5. Proposed Solar-Wind-Hydro Hybrid Electrical Supply

Table 2: Details of capital, replacement and O&M costs

List of component	Capital Cost	Replacement Cost	O&M Cost
Solar PV System (5 kW)	25000	25000	0
Wind Turbine (7.5 kW)	18750	18750	10
Hydro (1 kW)	12000	6000	1000
Converter (15 kW)	2100	2100	10

The configuration of the system components including the solar plant, wind turbine, hydro plant and the converters are illustrated in figure 6, 7, 8 and 9 respectively. The capital cost of $5/kW was considered for the solar system with no maintenance fees because solar panels require very insignificant maintenance. The system lifetime is fixed to 20 years. A 7.5 kW wind turbine was selected with the same lifetime of 20 years. The hydro plant was also configured with an average water flow of 100l/s and a total head of about 10m. The converter block is mainly used for the inverter function and its efficiency is set to 90%.

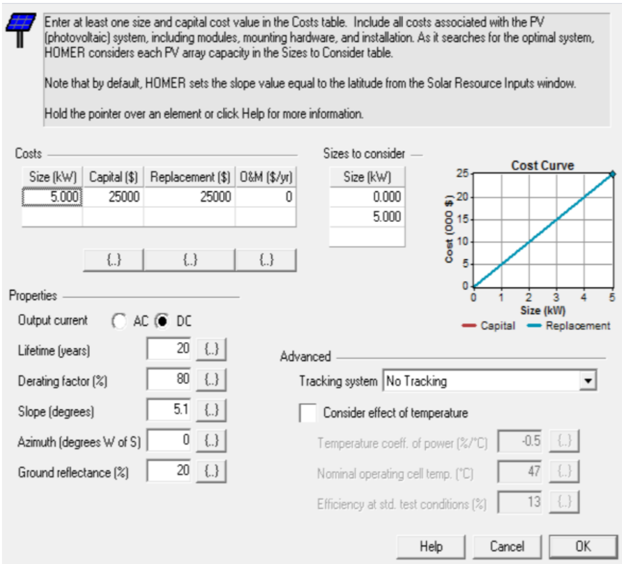


Fig 6. Configuration of Solar Plant

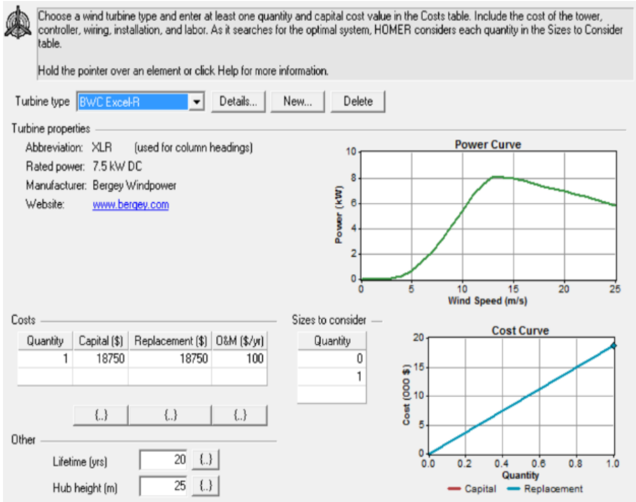


Fig 7. Configuration of Wind Turbine

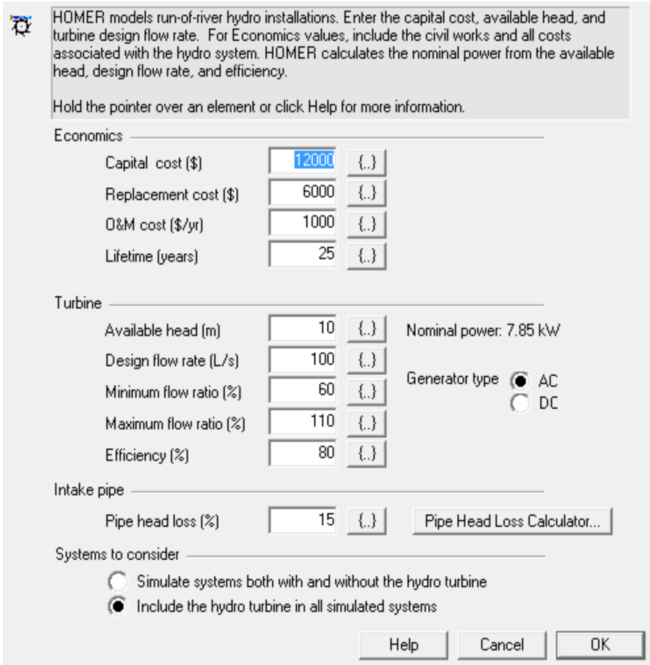


Fig 8. Configuration of Hydropower Plant

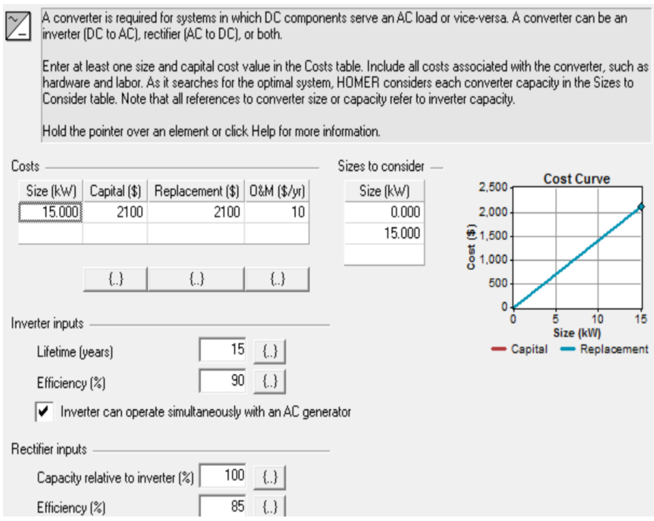


Fig 9. Configuration of Converter

3. RESULT AND DISCUSSION

Simulation results were obtained from both the proposed algorithm (implemented with Matlab) and also the implementation done with the Homer software. Figure 10 and 11 show the contribution of individual plants to the total energy supplied using respectively the self-developed optimization algorithm and the HOMER software.

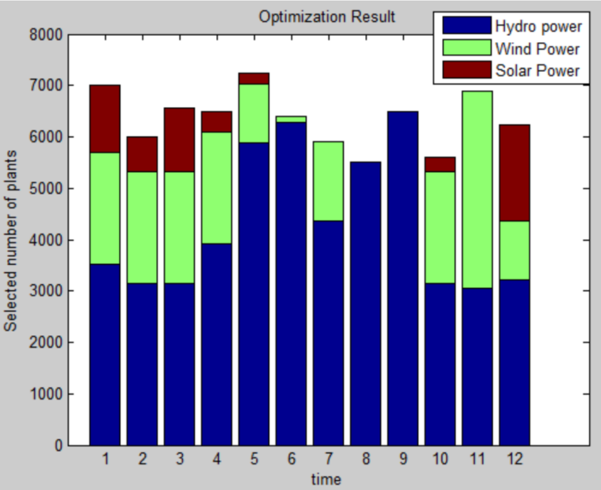


Fig 10. Contribution of individual plants to the total energy supplied using the self-optimized method

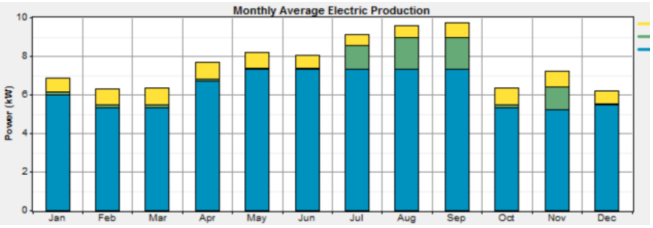


Fig 11. Contribution of individual plants to the total energy supplied using the HOMER

These graphs show actually the dynamic operation of the optimization methods in selecting the adequate sources and level of their contribution that brings the optimum cost. It is observed in both cases that the hydropower plant has been selected and used throughout the year. This is justified due to the cost of generating hydro which is the least as compared to the counterpart solar and wind. In reality, the unit cost of electricity estimated by the self-optimized algorithm were 0.64$/kWh, 0.52$/kWh, 0.36$/kWh respectively for the solar, wind and hydro energy. Subsequently, the other two sources becomes additive to compensate the load in case the hydro contribution is not enough to satisfy the request. In cases where the hydro energy produced can supply the load request, it is solely used as in the case of the eighth and ninth month (figure 10). It is also observed that the wind energy comes in second priority as its cost is lower than the solar one with respect to the self-optimized algorithm. However, wind speed are very low in the considered location therefore making the wind energy production to be very small.

Besides, solar is the most expensive and most available that comes in when both the hydro and wind resources are exhausted. Surprisingly, the solar is rather put in second priority in place of the wind with the HOMER optimization. With the HOMER result, the solar energy is often used in case of deficit of hydro energy and it is only when the solar is exhausted that the wind energy is solicited. Back to the settings, it can be observed that the capital for solar is $25000 with $0 for O&M and the wind capital is $18750 with $10 for O&M per year. With these facts, we therefore believe that the proposed algorithm approaches this aspect of the optimization in a better manner than the HOMER does.

Moreover, it must be observed that the dynamic contribution of individual sources do not follow strictly the same pattern in both cases of optimization and this is due to the random variability of energy resources (solar radiation, wind speed, available water flow) and load request that do not necessarily follow the same pattern in both cases.

Furthermore, figure 12 and 13 show the cost of electricity and the energy supply versus the load requested for both methods.

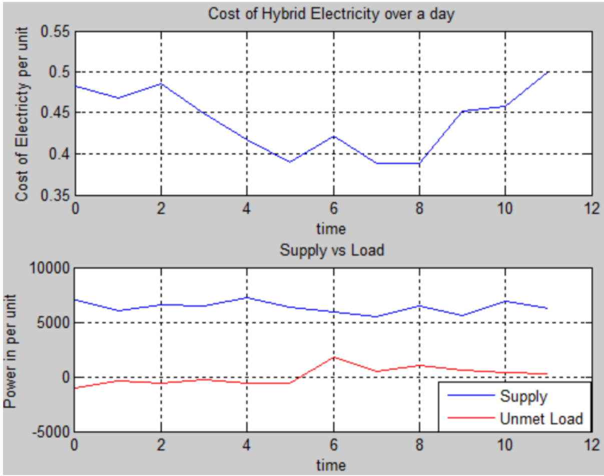
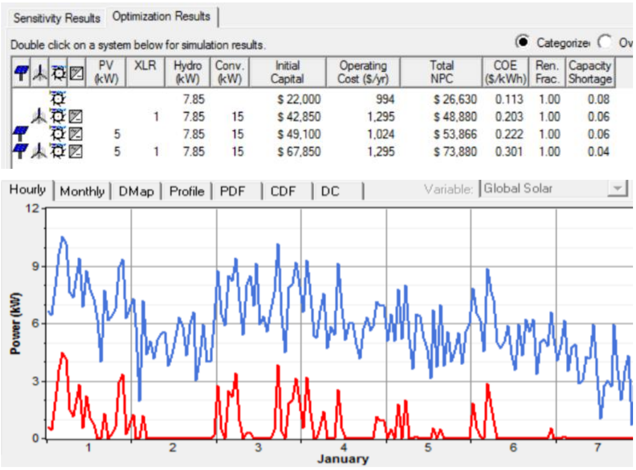


Fig 12. Cost of Electricity and Supply vs Load request using the self-optimized algorithm



PV (kW)	XLR	Hydro (kW)	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
		7.85		$ 22,000	994	$ 26,630	0.113	1.00	0.08
	1	7.85	15	$ 42,850	1,295	$ 48,880	0.203	1.00	0.06
5		7.85	15	$ 49,100	1,024	$ 53,866	0.222	1.00	0.06
5	1	7.85	15	$ 67,850	1,295	$ 73,880	0.301	1.00	0.04

Fig 13. Cost of Electricity and Supply vs Load request using the self-optimized algorithm

Figure 13 shows that the HOMER estimates an initial capital cost of $67850 with an operating cost of $1,295 per year for the proposed hybrid solar-wind-hydro power plant. The cost of electricity which is the main economic output of the HOMER optimization software is found to be 0.307$/kWh. On the other hand, figure 12 shows that the cost of electricity varies averagely around 0.442 $/kWh with a peak of 0.5 $/kWh. In general the cost estimated by the developed algorithm is roughly higher than the one estimated by the HOMER for the same conditions. This can be beneficial for the investor as it may reduce the payback period of the system while keeping the electricity cost affordable and acceptable to consumers.

Furthermore, a basic constraint for the optimization was to always satisfy the load request. This was achieved brilliantly in the second part of figure 12 where the unmet load is almost always closed to zero. The same situation is depicted in the second part of figure 13 where the curve in red represent the unmet load using the HOMER software. It appears clearly that majority of the load is satisfy with the first method as compared to the HOMER optimization.

4. CONCLUSION

In summary, this paper dealt with a comparative analysis of cost optimization of hybrid energy system comprising of solar, wind and hydro plants, using a self-developed algorithm and the HOMER optimization software. The optimization methods were presented and tested over the same data and results were compared. It was revealed that the self-optimized system shows more dynamism and rational in the selection of different sources as compared to the HOMER. The cost of electricity is however higher with the self-optimized method (0.442 $/kWh) than the HOMER (0.307 $/kWh) and this brings about a quicker payback period which is a big motivation for investors. Finally, the two methods were compared on the basis of satisfaction of the load request. It appears that the percentage of unmet load is higher with the HOMER than the self-optimized method. Cost optimization of hybrid system is very useful to reduce the cost of electricity while keeping profit in acceptable range. HOMER is the standard software used to achieve such optimization but this paper proposes a counter method that brings pertinent differences in the result obtained. Henceforth, there is a merit in researching more advanced optimization method to re-assess the cost benefit of Hybrid energy supplies.

5. APPENDIX

5.1 Matlab Code Showing the Self-Proposed Solution

```
clear all
clf
clc
%General Data
t=[0:11];
P_load=[7000,6000,6550,6500,7250,6400,5900,5500,6500,5600,6890,6240];
P_rload=randi([5500 7300],1,12);
Q = [90, 80, 80, 100, 150, 160, 111, 190, 185, 80, 78, 82];
 %Data on irradiation and wind speed at Accra
G = [4.1, 4.59, 5.21, 5.08, 5.02, 3.97, 3.7, 3.84, 4.59, 5.19,
4.79, 3.86];
Vw = [2.6, 2.6, 2.6, 2.6, 2.1, 2.1, 4.6, 5.1, 5.1, 2.6, 4.6, 2.1];
 % Loading initial data needed for the computation of unit
cost
% …
% End of data
% Computing unit cost of electricity per each source
Cans = Ccs*CRFs+Cos;
Canw = Ccw*CRFw+Cow;
Canh = Cch*CRFh+Coh;
Cus = Cans/Es
Cuw = Canw/Ew
Cuh = Canh/Eh
for i=1:12
%Input parameters
   P_load(i); %Load power request
   %P_min=; % Minimum power generated by the Hybrid
System
   P_max=20e3; % Maximum power generated by the Hybrid
System
%Defining number of existing plants
   Ns=..;
   Nw=..;
   Nh=..;
 %Solar parameters
   n =0.2; %efficiency
   As =2; %Solar Area metre square
   G(i);    %Solar Irradiation
   T =1;    %Duration T in hours
   %Wind parameters
   ro_a =1.23; %air density
   Aw =pi*3^3; %Area swept by the blades in metre square
   Cp =16/27;  %Betz Coefficient
   Vw(i);      %Wind velocity
    %Hydro parameters
   ro_wa =1; %water density
   g =9.81;  %gravity acceleration
   H=4;    %Total head
  % Computing power generated by each source
   Ps(i) = n*As*G(i)*1000;
   Pw(i) = (1/2)*ro_a*Aw*Cp*Vw(i)^3;
   Ph(i) = ro_wa*g*H*Q(i);
  % Defining the optimization problem
variables = {'as','aw','ah'};
N = length(variables);
% create variables for indexing
for v = 1:N
eval([variables{v},' = ', num2str(v),';']);
end
%Defining the lower bounds
lb = zeros(size(variables));
lb([as,aw,ah]) = [0,0,0];
%Defining the upper bounds
ub = Inf(size(variables));
ub([as,aw,ah]) = [Ns,Nw,Nh];
%Entrying linear inequality constraints
   A = zeros(2,3);
   A(1,[as,aw,ah]) = [-Ps(i),-Pw(i),-Ph(i)];
   b(1) = -P_load(i);
   A(2,[as,aw,ah]) = [Ps(i),Pw(i),Ph(i)];
   b(2) = P_max;
   %Linear Equality Constraints
   Aeq=[];
   beq=[];
      %Objective Function
   f = zeros(size(variables));
   f([as aw ah]) = [Cus*Ps(i)*T Cuw*Pw(i)*T Cuh*Ph(i)*T];
      %Solving the problem with linprog
   [x fval] = linprog(f,A,b,Aeq,beq,lb,ub);
   for d = 1:N
   fprintf('%12.2f \t%s\n',x(d),variables{d});
   end;
   aso(i)=x(1), awo(i)=x(2), aho(i)=x(3);
   P_Supply(i)=aso(i)*Ps(i)+awo(i)*Pw(i)+aho(i)*Ph(i);
   cost(i)=fval/P_Supply(i);
end
ao=[aho.*Ph;awo.*Pw;aso.*Ps];
figure(1)
bar(ao', 'stacked')
xlabel('time'), ylabel('Selected number of plants'),
title('Optimization Result')
legend('Hydro power', 'Wind Power', 'Solar Power');
 figure(2)
```

```
%subplot(2,1,1)
plot(t,cost),grid on
xlabel('time'), ylabel('Cost of Electricty per unit'), title('Cost
of Hybrid Electricity over a day')
%subplot(2,1,2)
%plot(t,P_Supply,t,(P_rload),'r'),grid on
%xlabel('time'), ylabel('Power in per unit'), title('Supply vs
Load')
%legend('Supply','Load')
```

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