IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 10, Issue 3 Ver. IV (May – Jun. 2015), PP 23-31
www.iosrjournals.org

Optimal Configuration of Wind/Solar/Diesel/Battery Hybrid Energy System for Electrification of Rural Area

Payal Suhane[1], Saroj Rangnekar[2], Arvind Mittal[3]
[1,2,3,]*(Energy Centre, Maulana Azad National Institute of Technology Bhopal, India)*

Abstract : *With the rapid deployment probability of fossil fuels and fast development of renewable energy technology, the renewable sources use are being promoted for various applications to reduce the consumption of fossil fuels. Integration of these sources as Hybrid Energy System (HES)* is better option *as a small scale alternative source of electrical energy. Wind/PV HES is more economical and reliable than a single PV or wind turbine for their complementary nature both in time and geography. And combination of these sources with diesel generator is better option for un-electrified remote areas as compare to diesel generator alone. Unpredictable nature of wind and intermittent nature of solar as well as variation in load demand introduces, complexity in HES, therefore sizing of HES is prerequisite for power supply to areas at minimum cost. In this paper, Jhiri village of Madhya Pradesh (India) is identified as un-electrified remote area to be considered for case study. Load profile creation of the above area is done based on the daily consumption of electricity as per the population and ensuring minimum possible electrification in present scenario. Optimal sizing of selected HES is done with the help of Homer software. An economical and reliable HES has been proposed for above area for betterment of human life and overall growth of the village.*

Keywords - *Renewable Energy Sources, Hybrid Energy System, PV array, Wind Turbine, Battery, Diesel Generator, Homer software*

I. Introduction

At present, India is a large consumer of fossil fuels. According to present energy consumption rate, coal reserves should last for about 200 years, oil for approximately 40 years and natural gas for around 60 years [1]. The majority of the energy requirement around the world now is dependent on fossil fuels for a big portion of their energy demand. Towering costs of these fuels have converted into remarkable increases in the cost of energy generation especially for rural areas [2]. For an un-electrified rural area if grid expansion is not economical viable than diesel generator is one of the alternative energy sources [3], if transportation is possible and economically feasible. But environmental concern and costly fuel issue has diverted concern towards hybrid configuration of diesel with other renewable energy sources. Due to natural unpredicable properties of wind and intermittent nature photovoltaic power, stand-alone wind and/or SPV energy systems normally require energy storage devices like battery, ultracapacitor and backup sources like diesel generator for increasing the quality and continuity of power supply [4]. Individual solar and wind can be integrated together in a hybrid system as they have complement nature and available naturally [5]. It reduces the percentage contribution of auxiliary source and has a say to clean-green environment policies

The idea is to maximize the powering of consumers by two ways i) renewable energy sources taken as main source and maintaining the continuity of supply by other backup-source during non availability of main source ii) all sources are renewable sources [6]. Wind-Diesel and solar-diesel hybrid system are studied for analyzing the performance of the overall system where diesel generator works as backup power source. Hybrid system can either be connected to Grid or as standalone system [7]. Stand alone system generally electrifies those areas far away from the grid and grid connected system used both as an load and source depending on the scenario, reducing the burden on main grid [8]. At present, Hybrid system consisting solar photovoltaic and wind systems have been promoted around the globe on a comparatively larger scale. Its development is driven by the government policy to reduce the greenhouse gas emissions and conserve fossil fuels. Reliability of the system can further be increased by adding a storage device or back up sources to successfully utilize hybrid power. HES in this paper include PV array system, WTg system, battery system and DG system for power generation and optimal sizing of HES is done with the Homer software for economical power generation [9].

II. Modeling Of Hes

The proposed structure of HES comprises of PV array, variable speed WT, battery and DG as shown in Fig.1. In this, wind and solar are integrated and complement each other as primary sources to meet the load requirements, DGs as an auxiliary source and battery backup storage for enhancing the reliability of system [10]. Modeling of components are explained in detail below.

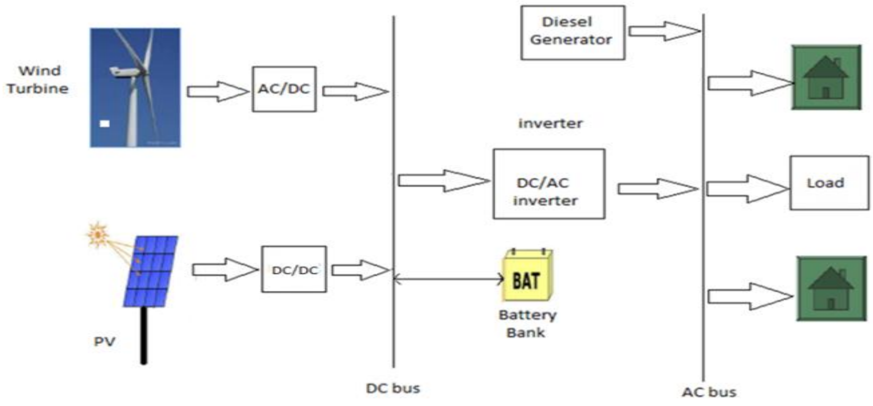

Fig1. Hybrid energy system

2.1Wind System Modeling:

The energy and output current of WT for each time instant is calculated on the basis of local weather conditions and actual installation height of turbines [9]. Fundamental equation governing the mechanical power capture of rotor blades of WT, which drives the electrical generator, is given by [11]:

$$P = \frac{1}{2}\rho A C_p V^3 \qquad (1)$$

where,
ρ : air density (kg/m^3)
A : area swept by the rotor blades
V : velocity of air (m/sec)
C_p : power coefficient of WT, it is often expressed as function of the rotor tip-speed to wind- speed ratio (TSR)

The power coefficient as a function of the tip-speed ratio and the blade pitch angle is defined below [10]:

$$C_p(\lambda, \theta) = c_1(c_2/\beta - c_3\,\theta - c_4\,\theta^x - c_5)\, e^{-c6/\beta} \qquad (2)$$

Since this function depends on the wind turbine rotor type, the coefficients c_1-c_6 and x can be different for various turbines. The proposed coefficient taken is equal to: c_1=0.5, c_2=116, c_3=0.4, c_4=0, c_5 = 5, c_6=21 (x is not used because c_4 =0). Additionally the parameter β is also defined by

$$1/\beta = 1/(\lambda+0.08\,\theta) - 0.035/(1+\theta^3) \qquad (3)$$

Where θ is the pitch angle[^{o}], which is the angle between the plane of rotation and the blade cross-section chord The tip speed of blade to wind speed ratio (TSR) is defined as follows:

$$\lambda = r\,\omega_g / V_\omega \qquad (4)$$

The Cp (λ, θ) characteristic, by taking the above parameters c_1-c_6 for various blade pitch angles θ, are presented in fig 2.

The tip speed of blades can be found through power curve of wind turbine for a corresponding wind speed. The wind turbine power curve is given in fig 1. At a given wind speed, the maximum energy conversion efficiency occur at an optimal TSR. Therefore as the wind speed changes, the turbine rotor speed needs to change accordingly in order to maintain the optimal TSR and thus to extract maximum power from the available wind resources. So optimal rotor speed can be found by (5)

$$\omega_{mopt} = \lambda_{opt}\; V_\omega / r \qquad (5)$$

2.2 Solar PV system Modeling:

The power of solar panel calculated on the basis of solar radiation value, derating factor considering various component losses and solar panel position to collect maximum radiation of Sun [12]. Based on the load voltage requirement specific number of panel is connected in series.

For a solar PV system the array voltage, including series parallel combination is given as [13]

$$V_a = -I_a\left(N_s R_s / N_p\right) + N_s K \log_e [\left(N_{sh} I_L - I_a + N_p I_o\right) / N_p I_o \qquad (6)$$

And array current

$$I_A = N_p[I_L - I_O\{\exp[q/AkT_c(V_A/N_s) + (I_A R_s/N_p)]\} - 1] - (N_p/R_p)[(V_A/N_s) + (I_A R_s/N_p)] \quad (7)$$

Here I_A is the PV array output current, I_L is solar cell photocurrent, I_O is solar cell reverse saturation current, V_A is PV array output voltage, q is charge of electron, A is P-N junction ideality factor (between 1 to 5), k is Boltzmann constant, T_c is absolute operating temperature of cell, N_s is number of cells in series, N_p is number of cells in parallel, R_s is series resistance of cell, R_p is parallel resistance of cell, and $K = nkT/q$

Regarding modelling of the PV system, there are many models to represent PV generator I-V characteristics. In PV generator model I_{ref} (reference output current) is chosen according to simplicity and four parameters found in manufacturer's data sheet (short circuit current I_{sc}, current at maximum power point I_{mp}, open circuit voltage V_{oc}, voltage at maximum power point V_{mp}) are employed . A PV generator I-V characteristic is represented by [32-36].

$$I_{ref} = I_{sc}\left[1 - C_1\{\exp(V_{ref}/C_2V_{oc}) - 1\}\right] \quad (8)$$

Here C_1 and C_2 are constants given in terms of I_{sc}, I_{mp}, V_{oc}, V_{mp} . V_{ref} is reference output voltage.
This equation can be adapted to other levels of irradiance and temperature and thereby V-I curve shifts accordingly. [33-34, 37]

$$\Delta T = T - T_{ref} \quad (9)$$

$$\Delta I = K_i\,(G/G_{ref})\,\Delta T + (G/G_{ref} - 1)\,I_{SC} \quad (10)$$

$$\Delta V = -K_V\Delta T - R_s\Delta I \quad (11)$$

So that

$$V_{new} = V_{ref} + \Delta V \quad (12)$$

$$I_{new} = I_{ref} + \Delta I \quad (13)$$

Where K_i and K_v are current and voltage temperature coefficients. Here G denotes solar radiation and T temperature.

Tilt angle 'β' which depends on latitude, sun's declination angle and insolation, can be obtained with help of following equation:

$$\beta = q(Vmp_{ref} + Imp_{ref} * R_s - Voc_{ref}) / KTc_{ref} * \log(1 - Imp_{ref}/Isc_{ref}) \quad (14)$$

Radiation and temperature dependence of I_L and I_O can be obtained with the help of following equations

$$I_L = Isc\,(T_{1ref}) * [G/G_{ref}] + K_O(T - T_1) \quad (15)$$

Where

$$K_O = [Isc\,(T_2) - Isc\,(T_1)] \,/\, (T_2 - T_1) \quad (16)$$

And temperature dependence of I_O

$$I_O = \frac{Isc\,(T_1)}{\left[e^{\frac{qVoc(T_1)}{nkT_1}}\right]\left(\frac{T}{T_1}\right)^{3/n}\left[e^{\frac{qVq_{T_1}}{nk\left(1/T - 1/T_1\right)}}\right]} \quad (17)$$

2.3 Battery System Modeling:

Battery stores the excess energy generated by HES and supply that energy during low generation period. If total output power of turbine and PV cell is greater than load power, then battery is in state of charging and the charged quantity of battery at the moment of (t) is given [12] by

$$P_b(t) = P_b(t-1).(1-\sigma) + [P_Z(t) - P_l(t)/\eta_{inv}]\,.\,\eta_{bc}$$

If total output power of turbine and PV cell is less than load power, then battery is in state of discharging and the charged quantity of battery at the moment of (t) is given by [8]:

$$P_b(t) = P_b(t-1).(1-\sigma) + [P_l(t)/\eta_{inv} - P_Z(t)]\,/\eta_{bf}$$

where,
$P_b(t)$: battery charged quantity at time (t)
$P_b(t-1)$: battery charged quantity at time (t-1)
σ : self-discharge rate per hour
$P_Z(t)$: total output power of turbine and PV cell in the time interval (t-1, t)
$P_l(t)$: total load power in the time interval (t-1, t)
η_{inv} : inverter efficiency
η_{bc} : battery charging efficiency
η_{bf} : battery discharging efficiency

2.4:Diesel System Modeling

DG power is related to fuel consumption means DG is characterized by its efficiency and its fuel consumption i.e. hourly and specific fuel consumption. Specific fuel consumption (l/kWh) is defined as the fuel consumption needed to produce 1 kWh of energy and it is equal to hourly fuel consumption (l/h) to supply a given load during 1h. Hourly fuel consumption is given by [6] :

$$q(t)=a.P(t)+b.P_r$$

where,
a : constant in l/kW for typical DG
b : constant in l/kW for typical DG
P(t) : power generated by DG in kW
P_r : rated/nominal power of DG in kW

III. Sizing Of Hybrid Energy System

The unit sizing of integrated power system plays an important role in deciding the reliability and economy of the system. For sizing of HES, prerequisite is load profile analysis, solar irradiance, variations in wind speed, temperature, and so forth as the metrological data is always changing and also vary from place to place. Climatic conditions determine the availability and magnitude of wind and solar energy at particular site. Pre-feasibility studies are based on weather data (wind speed, solar insolation) and load requirements for specific site [14]. The load side voltage is considered as 3 phase 415V, AC.

3.1 Load profile creation and metrological data collection

For load profile creation of rural area total population of remote area is considered as 1000 person. On the basis of power requirement of devices and instruments in houses, school, community centre street light, hospital and their predefined standard rating hourly load is calculated as shown in below fig 2 and monthly load profile is shown in fig 3.

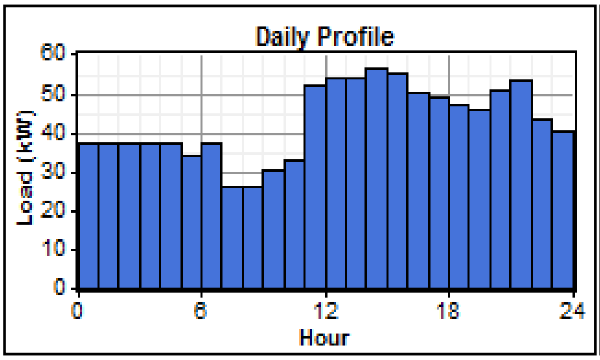

Fig2: Load daily profile

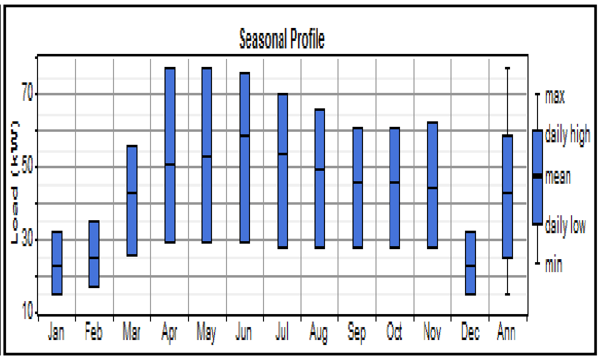

Fig3: Load monthly profile

Solar radiation and wind speed data is colledted from a data logger installed at MANIT. Bhopal (India) having latitude as $22^0 31'$ and longitude as $77^0 35'$. Monthly solar radiation, wind speed and temperature are shown in fig 4, fig5, and fig6 respectively.

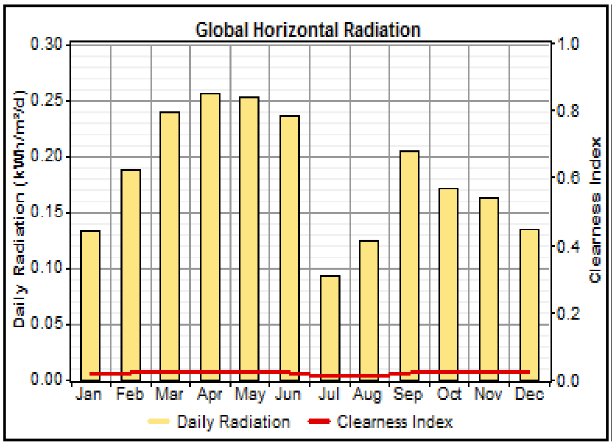

Fig4: Monthly avg. solar radiation

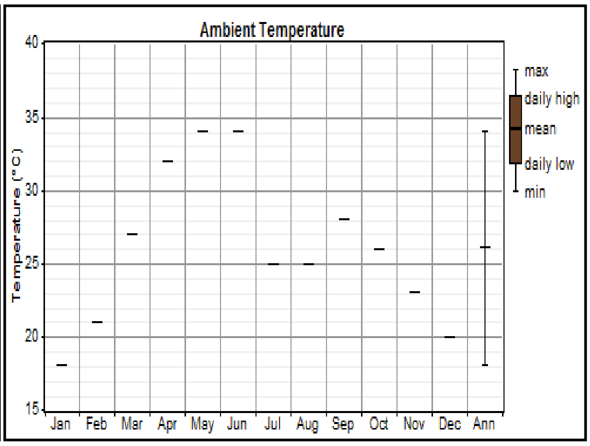

Fig5: Monthly avg. temperature

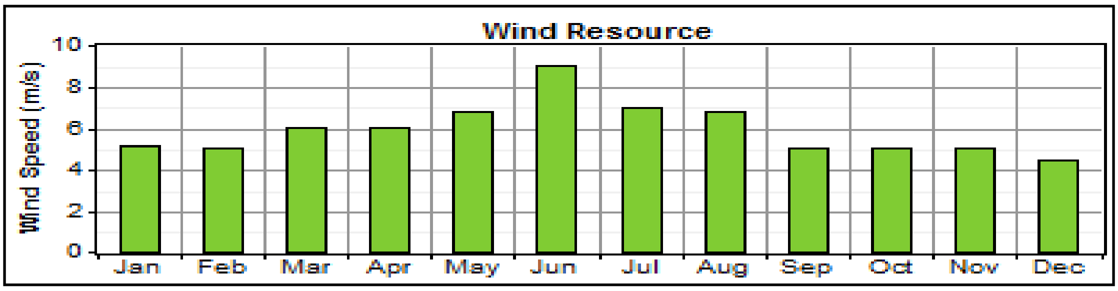

Fig6: Monthly avg. wind speed

3.2 Cost curve of HES devices:

For analysis of overall HES, component specification is given below. Individual costing components are included in software and cost curves for WTg, Solar PV panel, DGs and battery are shown in fig 7,fig 8, fig 9 and fig 10 respectively.

3.2.1PV panel specification:

Rated Power	250 W
Open circuit voltage	37.3 V
Short circuit current	8.30 A
Optimum voltage	30.8 V
Optimum current	8.71 A

3.2.2 WTg specification:

Rated power	5 kW
Cut-in speed	2.7 m/s
Cut-out speed	25 m/s
Rated power speed	10 m/s

3.2.3 DGs specification:

Rated capacity	10 KVA
Rated voltage	415 V

3.2.4 Battery specification:

Rated capacity	200 Ah
Rated voltage	12 V
Minimum state of charge	15 %

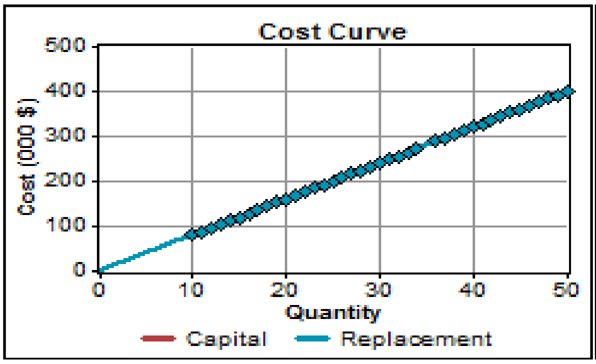

Fig7: PV panel cost curve

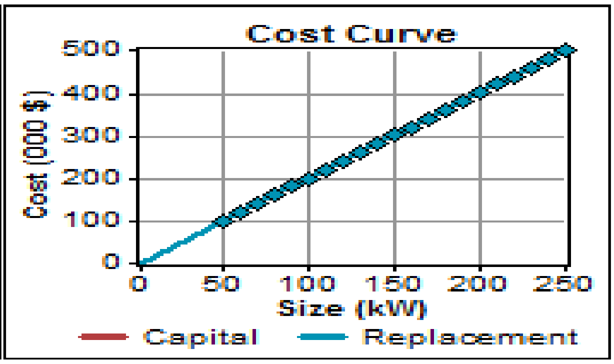

Fig8: WTg cost curve

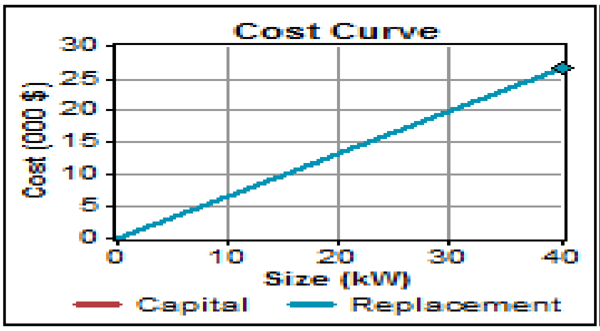

Fig9: Diesel generator cost curve

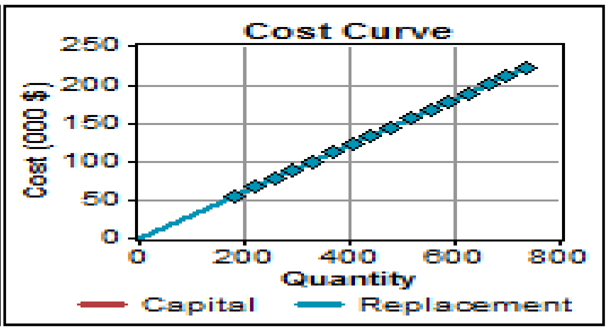

Fig10: Battery cost curve

3.3Optimal sizing of HES:

Sizing depends on various constrained requisite like renewable energy sources minimum capacity, diesel generator minimum capacity, battery capacity to supply the energy to load on unavailability of primary sources of system, Loss of Power supply Probability(LPSP) etc [15]. All the selected constrained is considered for optimal sizing with Homer Jhiri village for a specified LPSP the optimal sizing of the HES. The minimum capacities of components are decided based on following equations [16] [17]

3.3.1PV array installation minimum sizing is decided by average load required and

$Npvmin > avgLoad/ \eta pv$ (15)

ηpv: overall efficiency for PV array

maximum size is decided by maximum load requirement

$Npvmax < (MaxLoad/ \eta pv)$ (16)

3.3.2.Wind turbine minimum sizing is decided by average load required and maximum sizing is decided by maximum load required

$avgLoad < Nwt < (MaxLoad / \eta wt)$ (17)

ηwt: overall efficiency for wind turbine

3.3.3. Battery minimum sizing is decided to provide at least back power to load for λ number of days

$Nwt > \lambda * avgLoad$ (18)

λ: number of days

IV. Results And Discussion

Sizing of HES is done for two cases with and without battery storage backup and Homer results for both of the cases is discussed below.

4.1Case 1-With battery storage as backup:

Minimum backup storage has been considered as supplying power to load for four hours on non-availability of primary sources. Monthly average production of electricity is shown in fig 11 and optimal sizing Homer window in fig 12 and results for this case is complied in Table1.

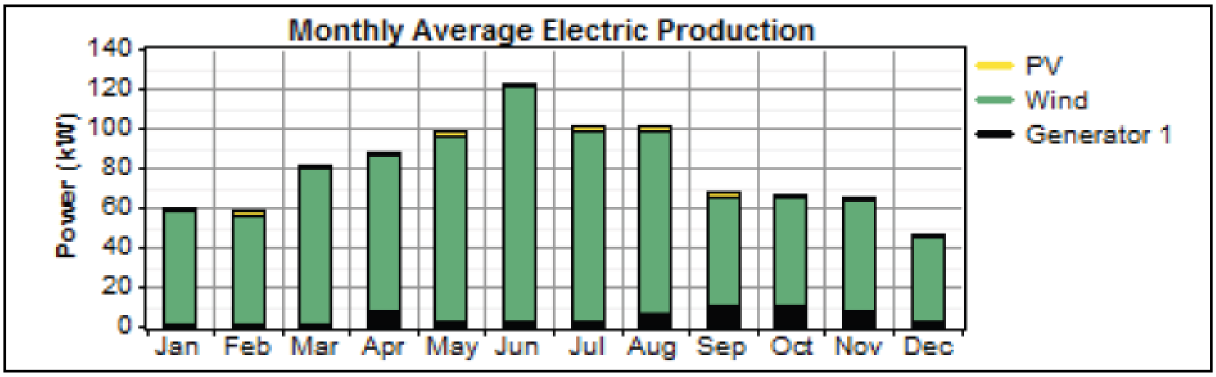

Fig11: Monthly avg. electricity production

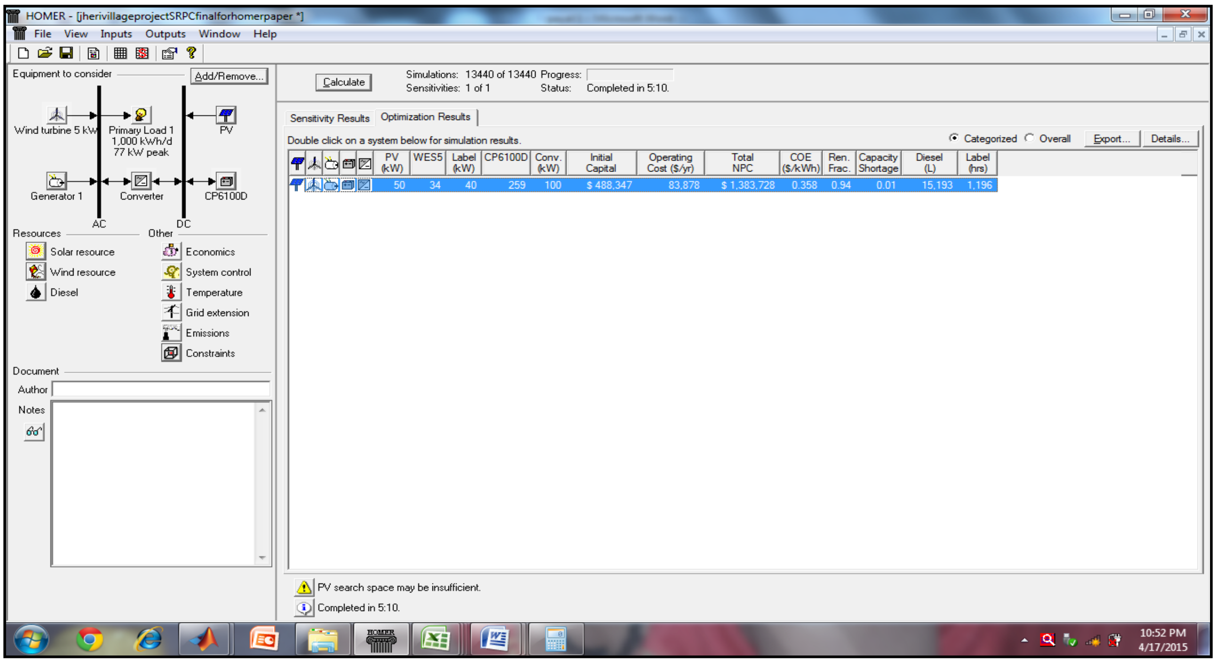

Fig12: Optimal sizing results from homer (with battery storage as backup)

Table 1: Detailed sizing and cost of each component (with battery storage as backup)

S.No.	Wind turbine	Solar PV panel	DG set	Battery	Converter (Inverter/ Rectifier)
Total sizing capacity	170 kW	50 kW	40 kW	52 kAh, 12 V	100 kW/100 kW
Total Investment Cost	170 Lakh	62 lakh	16.62 lakh	48.43 lakh	7 lakh
Total Operational Cost	90.72 lakh	26.62 lakh	102.12 lakh	43.1 lakh	4000/- Rs
Total Replacement Cost	0	0	0	201 lakh	4.75 lakh
Total fuel cost	0	0	93.5 lakh	0	0
Energy production in kWh/Year	639,880	17,396	44,677	86,657	0

5.2 Case2-Without battery storage:

In this case optimal sizing is done without specifying any minimum storage requirement. Monthly average production of electricity is shown in fig 13 and optimal sizing Homer window in fig 14 Sizing value of all sources and other components corresponding to minimum cost function are given in Table2.

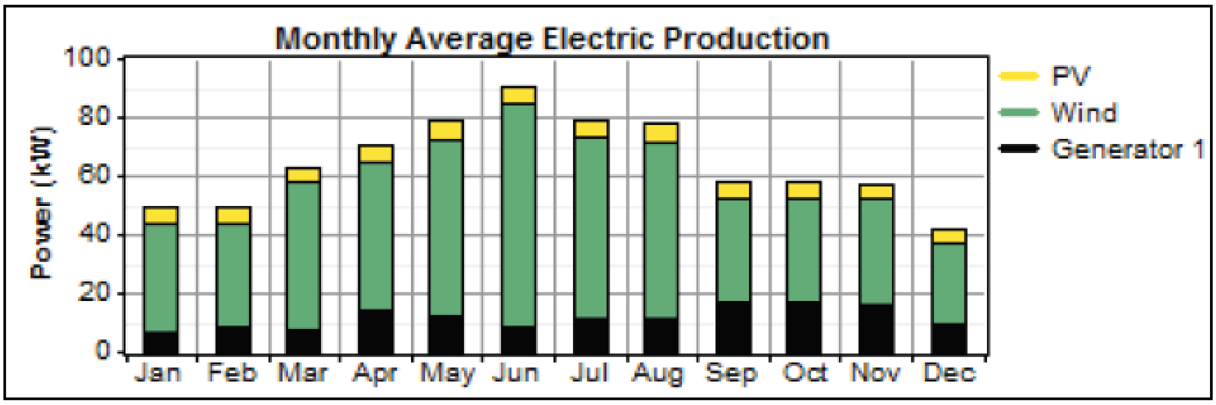

Fig13: Monthly avg. electricity production

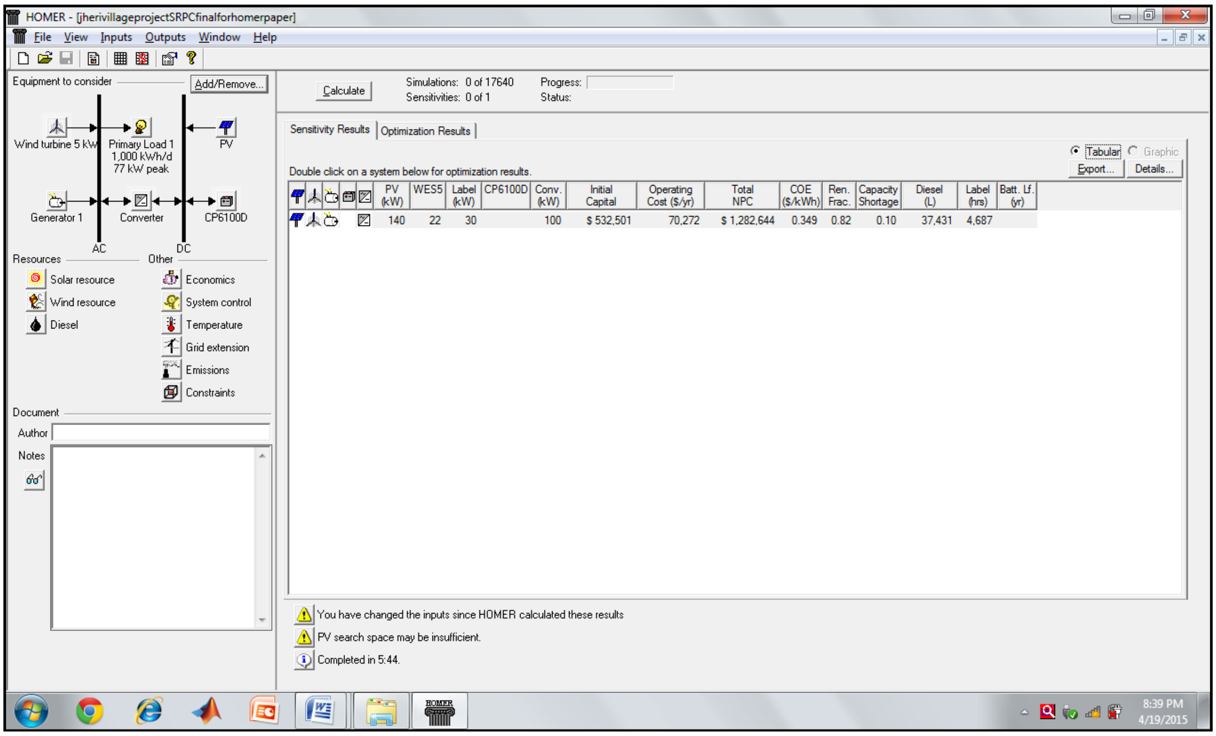

Fig14: Optimal sizing results from homer (without battery storage)

Table 2 : Detailed sizing and cost of each component (without battery storage)

S.No.	Wind turbine	Solar PV panel	DG set	Battery	Converter (Inverter/ Rectifier)
Total sizing capacity	110 kW	140kW	30kW	0	100kW/100kW
Total Investment Cost (in Rs)	137.1 lakh	174.5 lakh	12.46 lakh	0	7.79 lakh
Total Operational Cost (in Rs)	90.31 lakh	77.68 lakh	31.15 lakh	0	4674 Rs
Total Replacement Cost (in Rs)	0	0	15.11 lakh	0	5.28 lakh
Total fuel cost (in Rs)	0	0	230.37lakh	0	0
Energy production (kWh/year)	414,038	48,710	102,420	0	0

For analysis of both cases, sizing value of component is compiled in Table 3 for each scenario. On considering battery storage as backup for supplying average load power for specified hours, per unit cost of energy is increasing but increment in cost is compensated by Loss of Power Supply Probability (LPSP), which is around 1 % case 1 much less than as case 2 (10 %).

Table 2: Detailed sizing and cost of each component (without battery storage)

Software Homer	Wind turbine Size	Solar PV sizing	Battery sizing	DGs Sizing	Per unit cost of energy Rs/kWh	LPSP
Case 1	170 kW	50 kW	52 kAh, 12 V	40 kW	22.31	1 %
Case 2	110 kW	140 kW	0	30 kW	21.75	10 %

V. Conclusion

This paper discusses the optimal sizing of HES. Optimal sizing is done by taking into account the investment cost, operational cost and replacement cost of devices and fuel cost of DG set. The constraint for objective function is to electrify the selected area with reliable power at minimal cost. The obtained per unit energy cost of proposed system is much less as compare to diesel generator. The optimal sizing of system strongly depends solar and wind resource,(which can only be estimated on the basis of statistical data, or measured on site) and at the considered year of sizing, these has been taken into account. If large variation in the resource data occur than reliability of system can be reduced and results obtained may vary, therefore the application of above method may be limited to the pre-feasibility stage. However secondary source as DG set and battery backup storage are able to maintain the reliability of system if any acceptable variation occurs in resources data and load demand. Also inclusion of forecasting of these data, based on previous 5-10 years metrological data, can provide more appropriate figure as compared to considered one year data figure.

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