Proceedings of IOE Graduate Conference, 2016
pp. 277–285

An Approach to Wind-Solar Hybrid System Optimization for Rural Electrification in Nepal

Pukar Acharya [1], Jagan Nath Shrestha [2], Sudip Bhattarai [3]

[1, 3] *Department of Mechanical Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal*
[2] *Center for Energy Studies, Institute of Engineering, Tribhuvan University, Nepal*
Corresponding Emails: [1] pukar101@gmail.com, [2] shresthajn@gmail.com, [3] sudip@ioe.edu.np

Abstract

In this paper, a tool is proposed that can calculate optimum combinations of PV modules, wind turbines and battery bank for a wind-solar hybrid system using hourly average solar insolation, wind speed, temperature and load demand data based on levelized cost of electricity as the decision variable. For this study, Vorleni, Makwanpur 27°21'32.40"N and 85°27'58.74"E was chosen. In Vorleni, the study for socio-economic condition of community, system installed and nature of load were conducted. Hourly solar insolation and wind resource data and additional cost incurring factors were collected. Cost and technical information of PV modules, wind turbines and battery bank were collected from Alternative Energy Promotion Centre and contractors. Considering all the factors, a program for the optimization of wind-solar hybrid system was developed. For maximum levelized cost of electricity of NRs.25, the model yielded 10 combinations of wind turbines, PV modules and battery bank for the site condtion of Vorleni ranged from NRs.24.21 decreasing to NRs.11.94 corresponding the increase in the size of wind turbine. Increase in size of wind turbine resulted in the reduction of storage capacity required and size of PV modules thus, reducing the cost. Simulation results show that the program offers flexibility to the designer to choose the system as a compromise between cost and autonomy.

Keywords

Wind-Solar hybrid – electrification – Design Optimization – Levelized cost of Electricity

1. Introduction

1.1 Background

Alternative Energy Promotion Centre (AEPC) is giving high priority to wind-solar hybrid system for rural electrification after successful completion of first pilot project in Nawalparasi District, Nepal in December, 2011[1]. Wind solar hybrid system is a better option as compared to either solar PV or wind energy system alone in terms of reliability. Although three such projects has been completed so far by AEPC in Nawalparasi, Jumla and Makwanpur district respectively, a standard method has not been used to design these projects. This has given rise to several problems including the problem of synchronization of the wind and solar system. Thus, a proper standard optimized design is required in order to utilize the available energy resources, minimize the battery size and decrease the cost of electricity generation to make the system cost effective.

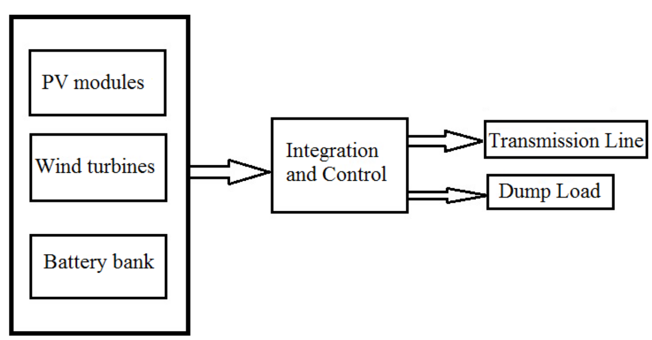

Figure 1: Block diagram of wind-solar hybrid System

In this paper, a case study of Vorleni, Makwanpur with the geographical co-ordinate of 27°21'32.40"N and 85° 27'58.74"E is presented where AEPC has already installed wind-solar hybrid system[2]. Figure 1, shows the typical block diagram of a wind-solar hybrid system. Dump load prevents the system from being damaged by providing alternative path for the excess energy when the battery is full charged.

1.2 Problem Statement

Wind-solar hybrid system is still a young technology in Nepal. Other than feasibility study and resource assessment, very little study has been conducted in the country in order to optimize such system. Moreover, AEPC which is the apex organization in the country working to implement this system for rural electrification does not yet have an optimized design methodology designed for the condition of Nepal to analyze the proposed design. In the official detailed feasibility report submitted to AEPC, the design method is not specified. If, optimum size of wind turbine, solar PV or battery capacity is installed; the resources can be utilized to their full extents. If the procurement, installation and operation cost are also included in the design consideration, best configuration can be achieved for any site.

1.3 Scope of the current study

A wind-solar hybrid system was installed in Vorleni by AEPC in 2013 based on a feasibility study conducted by a private consultant. Report submitted by the consultant proposed a configuration of 20.16kWp of solar PV modules, 15kW of wind turbines and 660kWh of battery bank for the site [2]. In this study, previously proposed design was checked to see if optimum combination was proposed using HOMER, which is a widely used tool for optimization and feasibility assessment of hybrid renewable energy systems. It gives more detailed optimization and sensitivity analysis with limited input [16]. Assumptions for resources and daily load demand of 119kWh were same as the previous design consideration. HOMER checked the optimum combinations for the site from the range of 10kW to 150kW for the size of PV module and wind turbine and size of battery up to 700kWh. One optimum combination of 30kWp of PV modules, 50kW of wind turbine and 200kWh of battery was proposed by HOMER which is significantly different from the initially proposed design. This result showed that the combination previously proposed is not considered optimum by HOMER.

However, HOMER only considers monthly average resource data for design. The design doesnot account the transitional fluctations in the resources for few days within a particular month which might affect the reliability of the design. If a tool would account hourly or even more frequent site data, the behaviour of the designed system could be simulated with increased accuracy and would also allow the designer to make the design modular as per the site requirements which can be an essential factor to consider while designing such system.

2. Methodology

2.1 Mathematical System Modeling

A mathematical tool was then developed in MATLAB for designing the optimum combinations using hourly average resource data for a period of one year. There are several sizing methodologies of wind- solar hybrid available. Some authors used probabilistic analysis approach for optimization. H. Yang et.al. used Loss of Power Supply Probability(LPSP) s sizing constraints[7][13]. G.M. Tina et.al. used Energy Index of reliability as sizing constraint [14]. Similarly, some others use Techno-economic approach for optimization. Celi et.al. used Cost/KWh, level of autonomy as sizing constraint[8]. Kouttroulis et. al used total cost and load energy requirement as constraint[10]. L Lu. et.al. and S. Diaf et.al. used LPSP and Levelized cost of Electricity as sizing constraints [11] [4]. Likewise, others use economic approach for optimization. D.K. Khatod et.al. used production cost [15], S.C. Gupta et.al. used LPSP and life Cycle cost [12], S. Kamel et.al. used Net Present Value[9] and A. Kaabeche et.al. Deficiency of power Supply Probability and Life Cycle Cost[3] as sizing constraints. In this research, an economic approach of sizing was proposed with Levelized cost of Electricity as sizing constraints. Simple models with first order equations were used during this research so that the data required for sizing combinations could be easily obtained. Different models in the tool are given below:

2.1.1 PV Module Model

The hourly output power of the PV generator with an area $A_{pv}(m^2)$ at a solar radiation on tilted plane module G_t(W/m^2) is given by:[3]

$$P_{pv} = \eta_{pv} X A_{pv} X G_t \tag{1}$$

Where, η_{pv} represents the PV generator efficiency and is given by[3][4]:

$$\eta_{pv} = \eta_r X \eta_{pc} X [1 - \beta(T_c – T_{cref})] \tag{2}$$

Where, η_r is the reference module efficiency, η_{pc} is the power conditioning efficiency, β is the generator efficiency temperature constant, T_{cref} is the reference cell temperature ($^\circ C$) and T_c is the cell temperature ($^\circ C$) and can be calculated as follows:[3] [4]

$$T_c = T_a + (\frac{NOCT - 20}{800}) X G_t \tag{3}$$

Where, T_a is the ambient temperature of the site($^\circ C$) and NOCT is the nominal cell operating temperature.$T_{a,NOCT}$ = 20$^\circ C$ and $G_{\beta,NOCT}$= 800 W/m^2 η_{pc}, for wind speed of 1 m/s[4]. β, NOCT and A_{pv} are parameters that depends on the type of modules and a obtained from PV module manufacturers [3].

2.1.2 Wind Turbine Model

The wind speed distribution for selected sites as well as the power output characteristic of the chosen wind turbine is the factor that has to be considered to determine the wind energy output. Choosing a suitable model is very important for wind turbine power output simulations.The most simplified model to simulate the power output of a wind turbine can be described by: [3][4]

$$P_w(V) = \begin{cases} P_r^{(\frac{V^2 - V_c^2}{V_r^2 - V_c^2})} & \text{if } V_c \leq V \leq V_r \\ P_r & \text{if } V_r \leq V \leq V_f \\ 0 & \text{if } Otherwise \end{cases} \tag{4}$$

Where, P_r is the rated electrical power, V_c is the cut-in wind speed, V_r is the rated wind Speed and V_f is the cut-off wind speed. Similarly, the speed of the wind also depends on the height. It can be described by: [4]

$$\frac{V(H)}{V(Href)} = (\frac{H}{H_{ref}})^{\alpha} \tag{5}$$

Where, H is the hub height of wind turbine, V (H) is the wind speed at wind turbine, V(Href) is the wind speed measured at the reference height H_{ref}. The value of $\frac{1}{7}$ is usually taken for α when no specific data is available[4].

2.1.3 Battery Model

The size of the battery was calculated from the maximum value of energy deficit throughout the year evaluated from the minimum value of State of Charge (SOC) using the following formula [6]

$$E_{batt} = \frac{SOCXDOA}{DODX\eta} \tag{6}$$

where, E_{batt} is the Size of battery, DOA is the no. of autonomy days and its value was assumed to be 1 in order to check the performance of design at minimum level of autonomy, DOD is the design depth of discharge; its value was considered to be 60% for this study and η is the efficiency of battery system; its value was assumed to be 80% for this study. Difference between generated energy and energy consumed E_{diff} is evaluated by using formula,

$$E_{diff}(t) = E_{pv}(t) X n_{pv} + E_w(t) X n_w – E_l(t) \tag{7}$$

State of charge at time t, SOC (t) is evaluated as;

$$SOC(t) = SOC(t-1) + E_{diff}(t) \tag{8}$$

Where $E_{pv}(t)$ and $E_w(t)$ is the energy produced by a solar module and wind turbine respectively at time t, n_{pv} is the number of PV modules and n_w is the number of wind turbines. $E_l(t)$ is the energy consumed by load at time t. SOC(t) is the state of charge at time t.' t' represents the hourly data and its value ranges from 1 to 365 X 24 = 8760.

Then, Battery size is calculated using the minimum value of SOC during the observation of 8760 data points which is the maximum energy to be delivered by the battery.

2.1.4 Reliability Model

The battery for a particular size of PV module and wind turbine was designed for maximum value of energy deficit throughout the year, for the given resources and load profile; the combination was assumed to supply the energy uninterruptedly throughout the year.

2.1.5 Economic Model

The levelized cost of electricity (LCOE) was used as a decision variable in order to check if the combination was optimum. It can be evaluated by: [5]

$$LCOE = \frac{\sum_{1}^{N}(C_{solar} + C_{wind} + C_{stor})}{E_{TOT}} \quad (9)$$

Where, E_{TOT} is the total energy poduced during the life of the projects. C_{solar}, C_{wind} and C_{stor} represents the cost associated with solar component, wind component and battery storge component of the wind-solar hybrid throughout the life of the project respectively calculated as:

$$C_{solar} = \sum_{1}^{n_s} C_{PV_j} + \sum_{1}^{N} C_{repair_{(i)},PV} + \sum_{1}^{n_s} C_{trns_j,PV} \quad (10)$$

$$C_{wind} = \sum_{1}^{n_w} C_{tur_j} + \sum_{1}^{N} C_{repair_{(i)},tur} + \sum_{1}^{n_s} C_{trns_j,tur} \quad (11)$$

$$C_{stor} = \sum_{1}^{n_b} C_{batt_j} + \sum_{1}^{N} C_{repair_{(i)},batt} + \sum_{1}^{n_b} C_{trns_j,batt} \quad (12)$$

Where, C_{PV}, C_{tur} and C_{batt} represents the equipment cost of PV modules, wind turbines and batteries respectively. C_{repair} and C_{trns} represents the yearly repair and mintenance cost and transportation cost associated with the equipments. Similarly, n_s, n_w and n_b represents the number of replacements of solar panels, wind turbines and battery bank respectively. And, N represents the total life of the project.

2.1.6 Overall Software Model

Following informations are required as input.

i. Hourly average data of solar insolation, wind speed and temperature of a place for a period of 1 year.
ii. Hourly load demand.
iii. Maximum size limit of wind and solar component for testing.
iv. General specification of unit PV module to be implemented.
v. General specification of unit Wind turbine to be implemented.
vi. Equipment cost, yearly maintenance cost, Site specific transportation cost for unit PV module.
vii. Equipment cost, yearly maintenance cost, Site specific transportation cost for unit wind turbine.
viii. Equipment cost, yearly maintenance cost, Site specific transportation cost for unit battery bank.
ix. Design depth of Discharge (DOD).
x. Maximum allowable Levelized cost of electricity.

Based on the above mentioned information, the software generates a number of possible sizing combinations and the cost associated with each of those combinations that is below the maximum limit of levelized cost of electricity. The designer can choose the best suited combination as per the requirements. Overall flow chart of the program is given in figure 3.

2.2 Data Collection

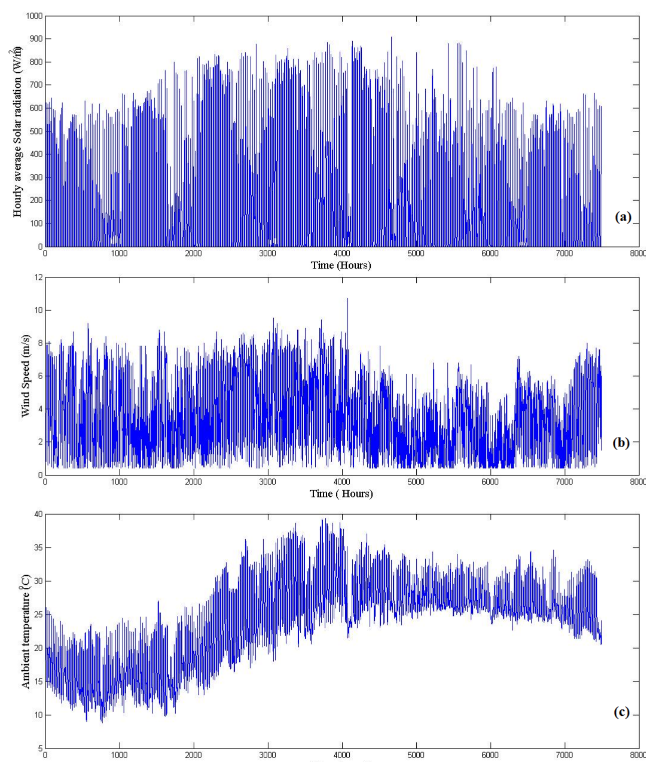

Figure 2: Hourly average resource data of Vorleni for a period of 1 year of(a) Solar Insolation (b) Wind Speed (c) Temperature

Hourly average data of wind speed, solar irradiance, temperature variation and load demand data of the

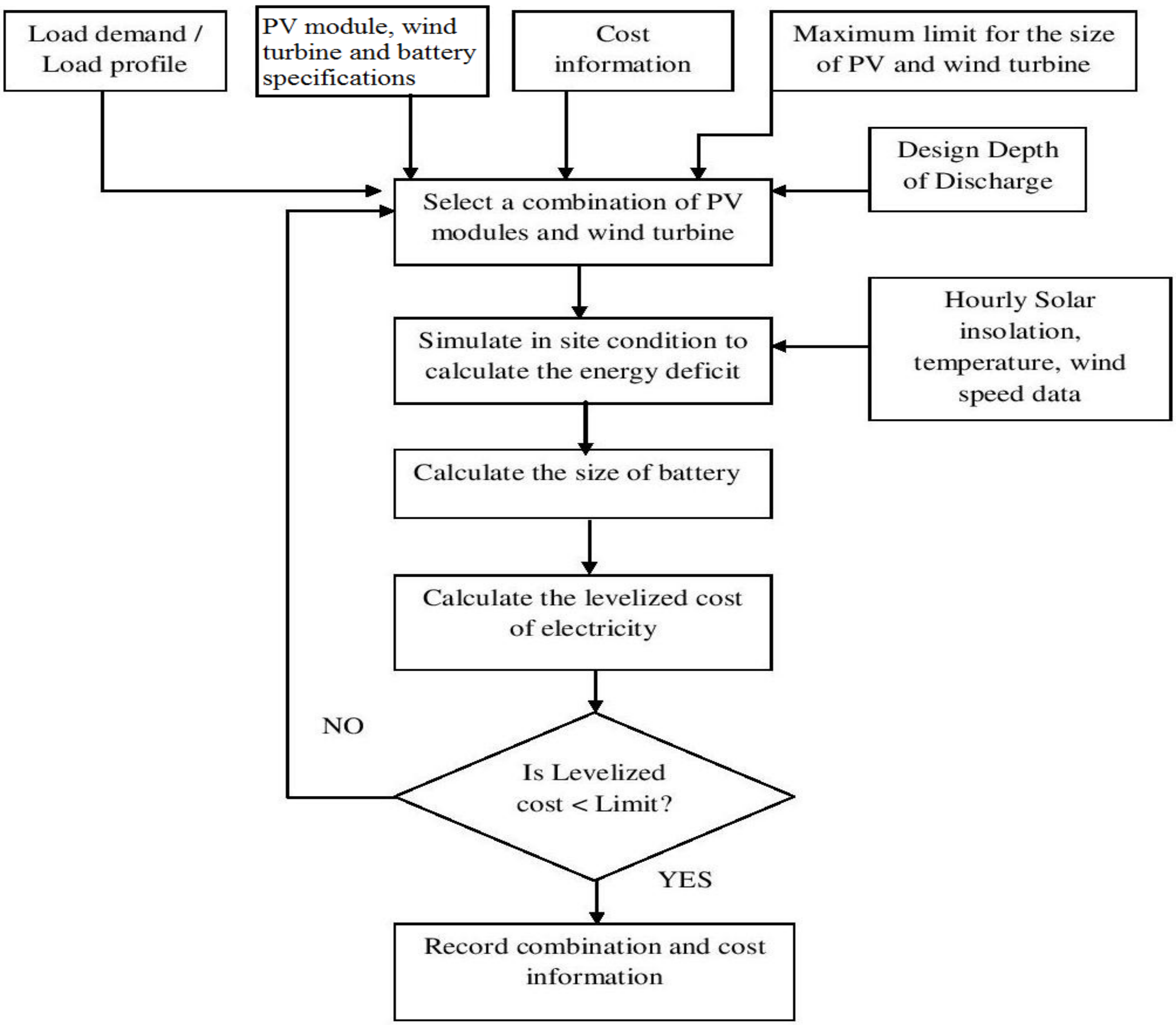

Figure 3: Flow chart of the program

Vorleni for a period of one year was collected from AEPC is shown in figure 2. These data were used to calculate the optimum combinations for Vorleni . The cost and technical specifications of PV modules, wind turbines and battery that are available in the market and are recommended for wind-solar hybrid systems were gathered from experienced contractors M/s. Topsun Energy Pvt. Ltd. and M/s. Krishna Grills and Engineering Works Pvt. Ltd.

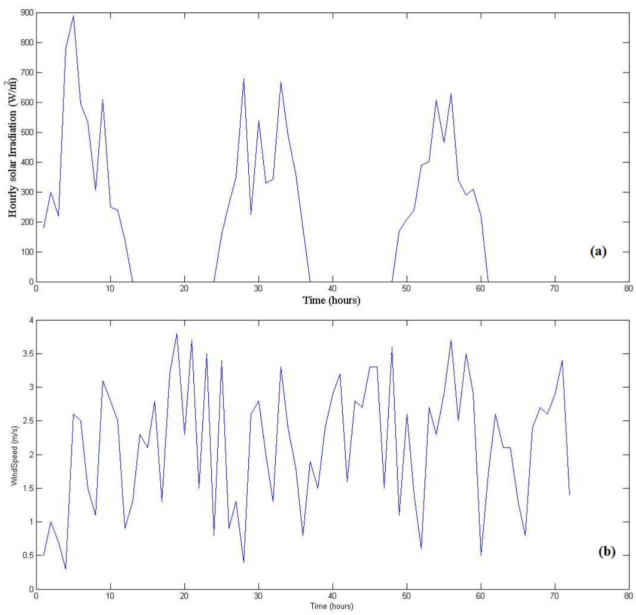

Figure 4: Hourly resource data collected from Vorleni during site visit (a) Solar Insolation (b) Wind Speed

Then, site visit to Vorleni, Makwanpur was conducted to get various information at site such as socio-economic profile, equipments installed, post implementational study, tarrif system, load nature, possibility of different cost incurring factors and primary resource data from site as shown in figure 4 used to test the results obtained from data during low resource condition as shown in figure 2. Findings were used to modify the model to incorporate the site specific factors to find the optimum combinations for the site. It was found during the site visit that the size of the system installed was not equal to the previously proposed design (i.e. 20.16kWp of PV modules, 15 kW of Wind Turbine and 660Wh of battery). Instead, Solar PV modules of 15.12kWp, wind turbine of 10kW and battery bank of 86.4kWh was installed. And the system installed could not fulfill the load demand during that period.

3. Results and Discussion

The cost information of previously proposed design for Vorleni was calculated. The total life cycle cost was found to be NRs.2,44,89,000 with levelized cost of electricity equals to NRs.24.31. Then, the optimum combinations for the site at 60% depth of discharge was calculated with levelized cost of electricity below NRs.25. Daily average load demand was assumed to be 119 kWh that is the exact same load assumption made for the site during previous design. In addition, in order to increase the reliability in design another condition was imposed; one type of resources should have atleast 10% of the total generation size of the combination. A list of combinations of PV modules, wind turbines and battery bank for the site were obtained that are given in Table 1. During this study, design calculations were made based on 7496 data points from the data obtained from AEPC. 1264 data points were neglected due to malfunctions in data logger at these hours. Since, the problem occurred at May and June which is the time of high solar and wind resource at the site, it should have minimum effect in the design.

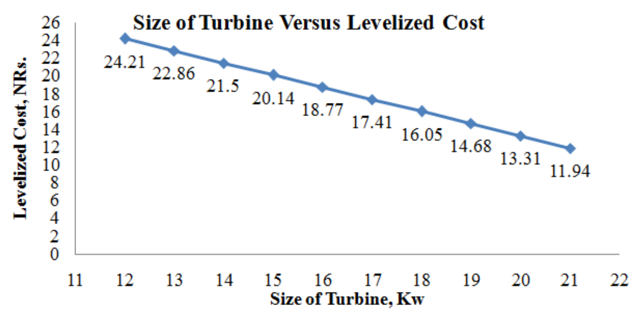

Figure 5: Variation of Levelized cost with size of wind turbine

It can be seen from Figure 5 that the resources of the site favoured the increase in size of wind-turbine for the same load . As, the size of wind turbine was increased, the size of PV modules and battery bank reduced thus, reducing the total life cycle cost as well as the levelized cost of electricity. However, the total energy generated from the system gradually decreased. The difference in total generated yearly energy between the most expensive and the list expensive design options was found to be

3.85kWh.

The cost information of the optimum combination given by HOMER(i.e. 30kWp of PV modules, 50kW of wind turbine and 200kWh of battery bank) was calculated in order to compare its output with the output of software developed. The total life cyle cost was found to be NRs.1,46,71,000 and the levelized cost of electricity was NRs. 6.08. The levelized cost of electricity for the combination given by HOMER was found to be significantly less than the best levelized cost of electricity obtained from the software developed during this resarch. However, the total life cycle cost of combination from HOMER lied between the 4^{th} and 5^{th} best cost effective combination obtained from the software.

3.1 Validation of Results

The results obtained from the site was tested using site data from Vorleni recorded during the site visit from July 19 to July 21 at the time of peaked monsoon. This was the time with probably the worst solar and wind resource at the place according to the locals.That is why this was the best time to test the effectiveness of the design and see the behaviour of each combinations. Each of the 10 options were simulated in the site condtion during the site visit period with the assumption of initial state of charge of battery bank being full. The plots obtained for each combinations are shown in figure 7. In addition, the combination received from HOMER, currently installed system as well as previously proposed design for the site was simulated in the site condition as well using the software. The plots obtained are shown in figure 6.

In figure 6(a), which simulates the existing system installed at site, the SOC drops below the SOC limit within the observation period. This explains why the system couldnot satisfy the load demand at low resource condition as observed during the site visit. In figure 6(b), which simulates the system proposed by HOMER, the SOC remains full during most of the observation period. Considering the low resources during that period, the amount of excess energy produced by this combination is high which is most likely wasted unless there is high prospects of productive load. Now, in case of figure 6(c), which represents the variation of SOC for the previously proposed design; the SOC variation of SOC is almost identical to the pattern seen in the figure 7(a) to figure 7(d). Beyond that, the fall in SOC seems greater in other options as compared to the previously proposed design.

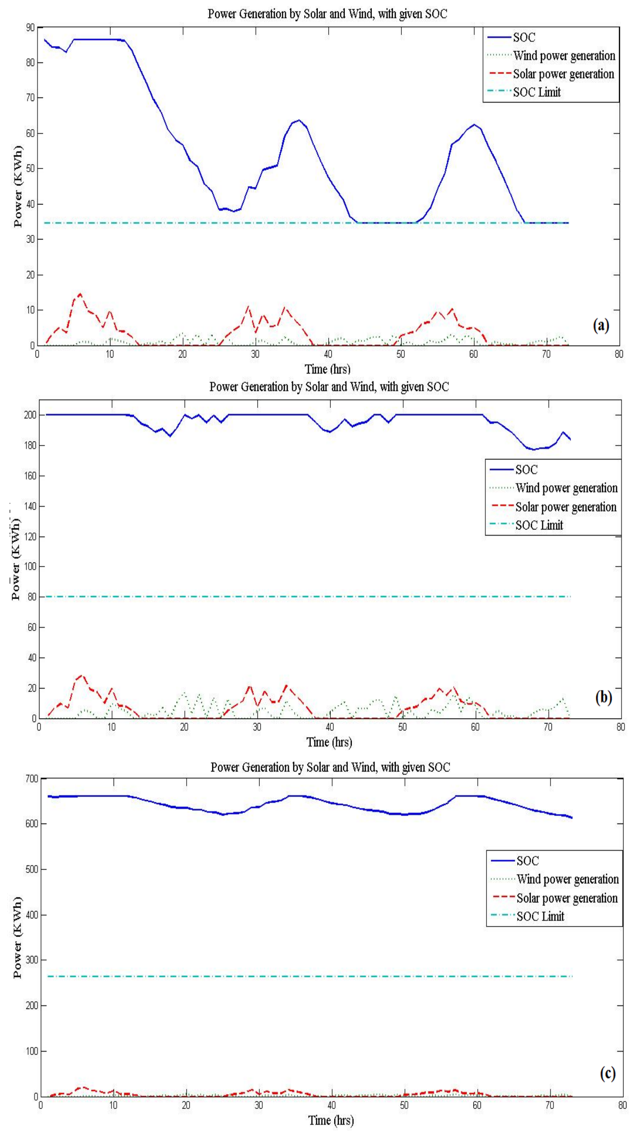

Figure 6: The plot of State of charge (SOC) simulated for (a) Existing system, (b) Combination from HOMER, and (c) Previously proposed design

In case of figure 7(a), the battery bank for option 1 more or less maintains the full state of charge despite of low resources. From figure 7(a) to 7(j), the state of charge (SOC) gradually decreases during the observation period of 72 hours. The fall in the level of SOC is maximum for option 10 as shown in figure 7(j). However, it is roughly at over 50% of the total storage capacity and thus satisfying the design consideration of 60% depth of discharge during the observation period.

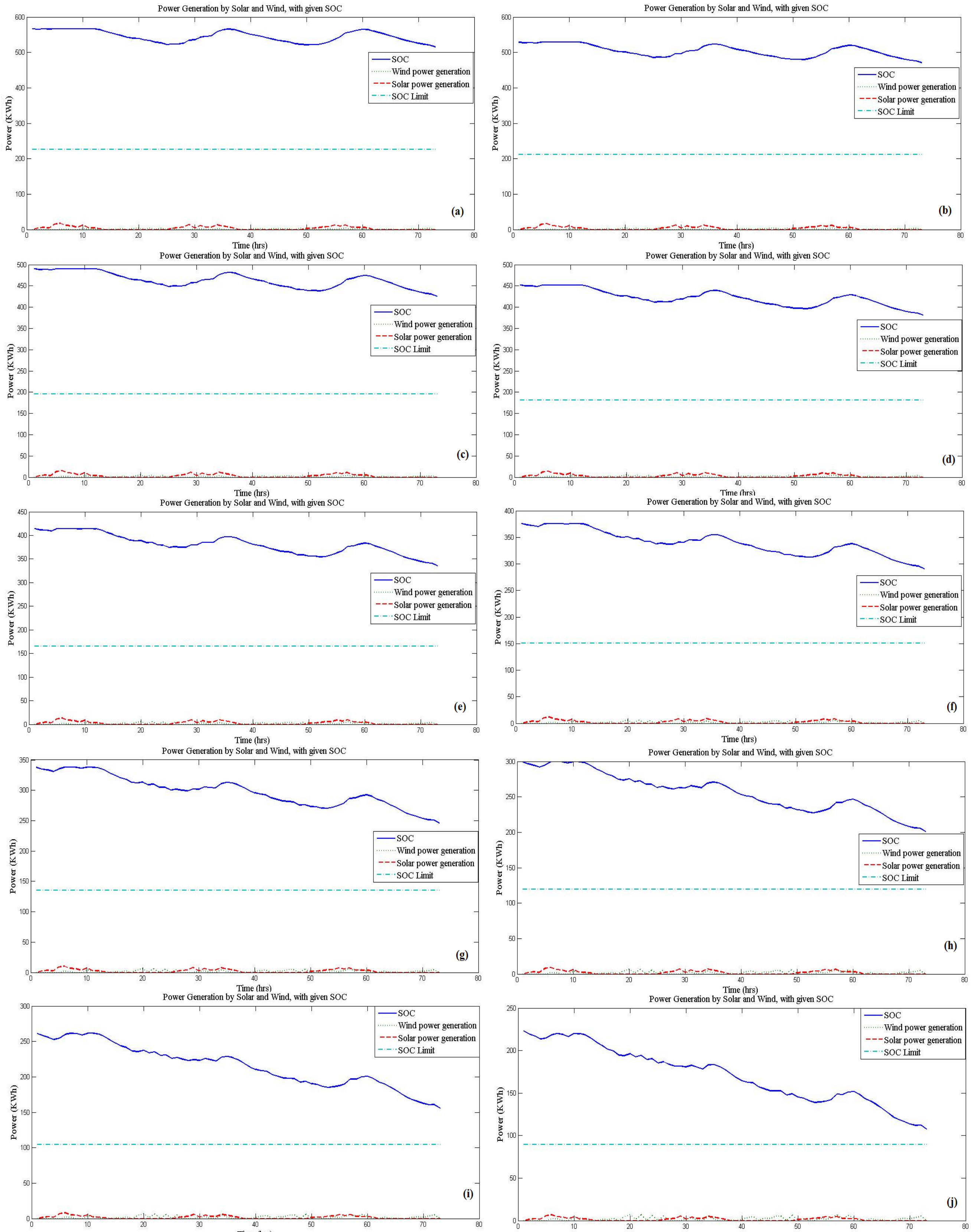

Figure 7: The plot of State of charge (SOC) simulated for (a) option 1, (b) option 2, (c) option 3, (d) option 4, (e)option 5, (f) option 6, (g) option 7, (h) option 8, (i) option 9 and (j) option 10

Table 1: Optimum conditions for Vorleni Makawanpur

Option no.	SolarSize(kWp)	WindPower(kW)	Battery(kWh)	Levelised Cost (Rs)	Total Life cycle Cost(Rs)	Total generated energy per year(kWh)
1	18.72	12	566.62	24.21	2,11,93,000	46,927
2	17.42	13	528.47	22.8 6	1,99,95,000	46,685
3	16.12	14	490.31	21.50	1,87,96,000	46,443
4	14.82	15	452.15	20.14	1,75,97,000	46,201
5	13.52	16	413.99	18.77	1,63,98,000	45,960
6	12.22	17	375.84	17.41	1,52,00,000	45,718
7	10.92	18	337.68	16.05	1,40,01,000	45,476
8	9.62	19	299.53	14.68	1,27,78,000	45,234
9	8.32	20	261.37	13.31	1,16,04,000	44,992
10	7.02	21	223.21	11.94	1,03,84,000	44,750

4. Conclusion

This paper presented a wind-solar hybrid system optimization tool which uses Levelized cost of electricity as the decision variable and then, a case study of Vorleni, Makwanpur to test the tool.Following conclusions were based on this study:

1. The model produced 10 economical designs for Vorleni as compared to previously proposed design with levelized cost of electricity equals to 24.31 which were as low as NRs.11.94.
2. As the size of wind turbine increased from 12kWto 21kW, the battery size required gradually reduced from 566.62kWh to 223.62kWh with simultaneous decrease in the size of PV modules from 18.72kW to 7.02kW.
3. Total generated energy per year however decreased along with the cost of the proposed system with 46,927 kWh produced by the most expensive option to 44,750 kWh produced by the most economical option.
4. Simulation during low resource condition shows that the autonomy of the system increases with the increase in storage capacity.
5. Thus, the current tool also offers flexibility to the designer to choose the system size as a compromize between the cost and autonomy.

References

[1] R.C. Poudel, et. al. *Reliability Evaluation of Small Standalone Hybrid Solar PV-Wind Power System*. Asian Development Bank, 2011.

[2] Mannings Consult Pvt. Ltd. *Detail Feasibility Study Wind-Solar Hybrid Project Bhorleni Village, Makwanpur, Nepal*. Alternative Energy Promotion Centre, 2013.

[3] A. Kaabeche, et. al. *Sizing optimization of grid-independent hybrid photovoltaic/wind power generation system*. ELSEVIER, 1214-1222, 2011.

[4] S. Diaf, et. al. *Design and techno-economical optimization of hybrid PV/wind system under various meteorological conditions*. ELSEVIER, 968-987, 2008.

[5] International Energy Agency *Costs of Generating Electricity*. Organization for Economic Co-operation and Development, 2005.

[6] Leonics: How to DesignSolar PV system, *http://www.leonics.com/~uno/articles2_12j_en.html*

[7] H. Yang, et. al. *Optimal sizing method for stand-alone hybrid solar-wind system with LPSP technology by using genetic algorithm*. ELSEVIER,354-367, 2008.

[8] Celi, et. al. *Techno-economic analysis of autonomous PV-wind hybrid energy systems using different sizing methods*. ELSEVIER,1951-1968, 2003.

[9] S. Kamel, et. al. *The economics of hybrid power systems for sustainable desert agriculture in Egypt*. ELSEVIER,1271-1281, 2005.

[10] E. Koutroulis, et. al. *Methodology for optimal sizing of stand-alone photovoltaic/ wind-generator systems using genetic algorthm*. ELSEVIER,1072-1088, 2006.

[11] L. Lu, et. al. *A Novel Optimization sizing model for hybrid solar-wind power generation system*. ELSEVIER,76-84, 2007.

[12] SC Gupta, et. al. *Optimal sizing of solar-wind hybrid system*. ELSEVIER,282-287, 2007.

[13] H. Yang, et. al. *Optimal design and techno-economic analysis of a hybrid solar-wind power generation system*. ELSEVIER,163-169, 2009.

[14] G.M. Tina, et. al. *Probabilistic modelling of hybrid solar/wind power system with solar tracking system*. ELSEVIER,1719-1729, 2011.

[15] D.K. Khatod, et. al. *Analytical Approach for Wel-Being Assessment of small Autonomous Power Systems With Solar and Wind Energy Sources*. IEEE TRANSACTIONS ON ENERGY CONVERSION,535-545, 2011.

[16] S. Paudel, et. al. *Optimization of Hybrid PV/Wind Power System for Remote Telecom Station* . IEEE, 2011.