Simulation and Optimization of Solar Photovoltaic-Wind stand alone Hybrid system in Hilly Terrain of India

Rahul Rawat*, S. S. Chandel**‡

* Centre for Energy and Environment,

National Institute of Technology, Hamirpur, Himachal Pradesh, India-177005

(rawatktp@gmail.com, chandel_shyam@yahoo.com)

‡ Corresponding Author; S. S. Chandel, National Institute of Technology, Hamirpur, Himachal Pradesh, India-177005, Tel.: +91-1972-254748, chandel_shyam@yahoo.com

Received: 12.06.2013 Accepted: 09.07.2013

Abstract- Wind and solar are clean energy sources with vast potential to reduce the dependence on conventional energy sources. The stochastic nature of these energy sources, has led to the development of reliable hybrid systems in recent years. The main objective of this paper is to utilize the available wind and solar resource to meet the energy needs of residential/institutional buildings in Western Himalayan Indian state of Himachal Pradesh. A 6 kWp solar-wind hybrid system installed on the roof top of an institutional building is analyzed and optimized using HOMER software at different reliability levels. The total electricity production by the system is found to be 1996 kWh/yr with cost of energy (COE) as $1.156/kWh . The techno-economic characteristics of existing and optimum hybrid system configurations with 0%, 5%, 10 and 20% maximum capacity shortage are studied. The influence of capacity shortage on total net present cost and excess electricity production is studied by sensitivity analysis of the hybrid system. A 2 kWp PV system with 1 string of ten 12V batteries, is found to be more economical than the existing system, with COE as $0.575 1/kWh. The optimum combination for utilizing the available solar and wind resource of the site is found to be a 5 kWp wind turbine, 2 kWp PV and battery storage. The results indicate that solar and wind resource can be utilized economically using solar-wind hybrid energy systems for decentralized applications in the Western Himalayan complex terrain. Further research areas are also identified.

Keywords- Hybrid energy system, Solar energy, Wind Energy, HOMER, Power generation, Himalayan region.

1. Introduction

The global warming, depletion of conventional energy sources and continuous increase in oil prices, have drawn worldwide attention for the development and utilization of renewable energy sources. The renewable energy sources are clean energy sources which can meet the energy demands without causing environmental pollution. Wind and solar sources have vast potential to reduce the dependence on conventional energy sources, however, the stochastic behavior of both these energy sources, is a major drawback [1]. Solar energy is available only on clear day while wind speed is very intermittent as such, for a reliable power supply, hybrid power generation is the best option. The integration of solar and wind energy systems into a hybrid system improves the reliability, reduces the energy storage requirement and overcomes the over sizing problem, but also enhances the degree of complexity of the system [2-3]. The optimal sizing of each component of hybrid system is required to make the system technically as well as economically feasible and efficient [4-8].

A number of authors have used Hybrid Optimization Model for Electric Renewables (HOMER) for optimizing hybrid systems for different locations worldwide [9-13]. HOMER is found to be one of the most widely used software for the optimization and sensitivity analysis of hybrid systems [14]. The inputs required for the analysis are solar radiation, wind speed, temperature data, load profile, constraints, system control and economic factors [15].

A 5 kWp wind 1 kWp solar photovoltaic (PV) standalone hybrid system with battery storage was installed in 2012 as an experimental demonstration system at the Centre for Energy & Environment (CEE), National Institute of Technology (NIT), Hamirpur, Himachal Pradesh, India. This system was procured and installed without any optimization and detailed resource analysis of the site. This system is first of its kind installed in the mid hill region of the western Himalayan state of Himachal Pradesh and as such presents an interesting opportunity to study the effectiveness of hybrid systems for power generation in hilly regions. Keeping in view this aspect, the 6 kWp hybrid system is analyzed and optimized using HOMER at different reliability levels. The various optimized system configurations based on reliability, have been identified.

The paper is organized as follows: next section presents specifications of the 6 kWp solar wind hybrid system; the methodology is given in section 3; Results are presented and discussed in section 4 followed by conclusion in last section.

2. Solar-Wind Hybrid Experimental System Description

A 6 kWp solar - wind hybrid system consisting of 1 kWp solar PV, 5 kW wind turbine, 4 kW converter and 150 Ah battery bank, is installed on the rooftop of CEE, NIT Hamirpur building (latitude :31°41' N and longitude :76°31'E in GMT + 5:30 time zone, altitude : 892.7 m above sea level) (Fig. 1).

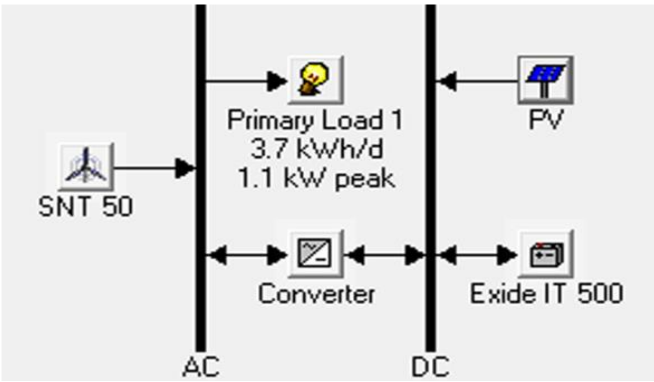


Fig. 1. 6 kWp Solar -Wind hybrid system configuration

1 kWp south facing PV array consisting of 10 polycrystalline silicon PV panels of 100 W_p each, are mounted at 30°. The PV module specifications at standard test conditions along with economic parameters are given in table 1.

Table 1. PV system specifications

Description	Specification
PV module material	Polycrystalline
Peak power (Pm)	100 Wp
Voltage at peak power (Vm)	17 V
Current at peak power (Im)	5.9 A
Open circuit voltage (Voc)	21 V
Short circuit current (Isc)	6.4 A
Efficiency	13%
Capital cost of PV system	$ 5057
Replacement cost of PV system	$ 5057
Operation and maintenance cost	$ 0
Estimated lifetime	25 years

A 5 kWp horizontal axis micro wind turbine SNT-50 model of Supernova Technologies, India with hub height 28.5 m is used to utilize the wind resource for power generation. The technical and economic parameters of the wind turbine are given in Table 2.

Table 2. 5 kWp wind turbine specifications

Description	Specifications
Rotor diameter	6.09 m
Rated power	5 kWp
Cut-in wind speed	2.5 m/s
Equivalent rated wind speed	11 m/s
Blade material	Fibre-reinforced plastic (FRP)
Generator type	Permanent magnet 3 phase alternator
Tower	Tripod structure
Capital cost	$ 15016
Replacement cost	$ 7038
Operation and maintenance cost	$ 70
Estimated lifetime	25 Years

Due to intermittent nature of both solar and wind energy, energy storage is needed to supply electric power continuously. A battery bank of 150 Ah rated capacity is used for energy storage in this system. The 120 V battery bank consists of ten 12 volt Exide inva-tubular IT-500 lead-acid batteries, connected in series.

The electricity produced by the hybrid system is supplied to faculty rooms and office of CEE, NIT Hamirpur. The remaining power after serving the load is stored in the battery bank. The hourly load profile of CEE being catered by the hybrid system for the entire year is shown in Fig. 2. The load demand is less during summers, as only office remains open in the month of June-July due to vacations. The average daily load demand, average energy demand, peak load demand and load factor of the building are 0.156kW, 3.75kWh/d, 1.15kW and 0.136 respectively. The daily and hourly random variability of load is taken as 10%.

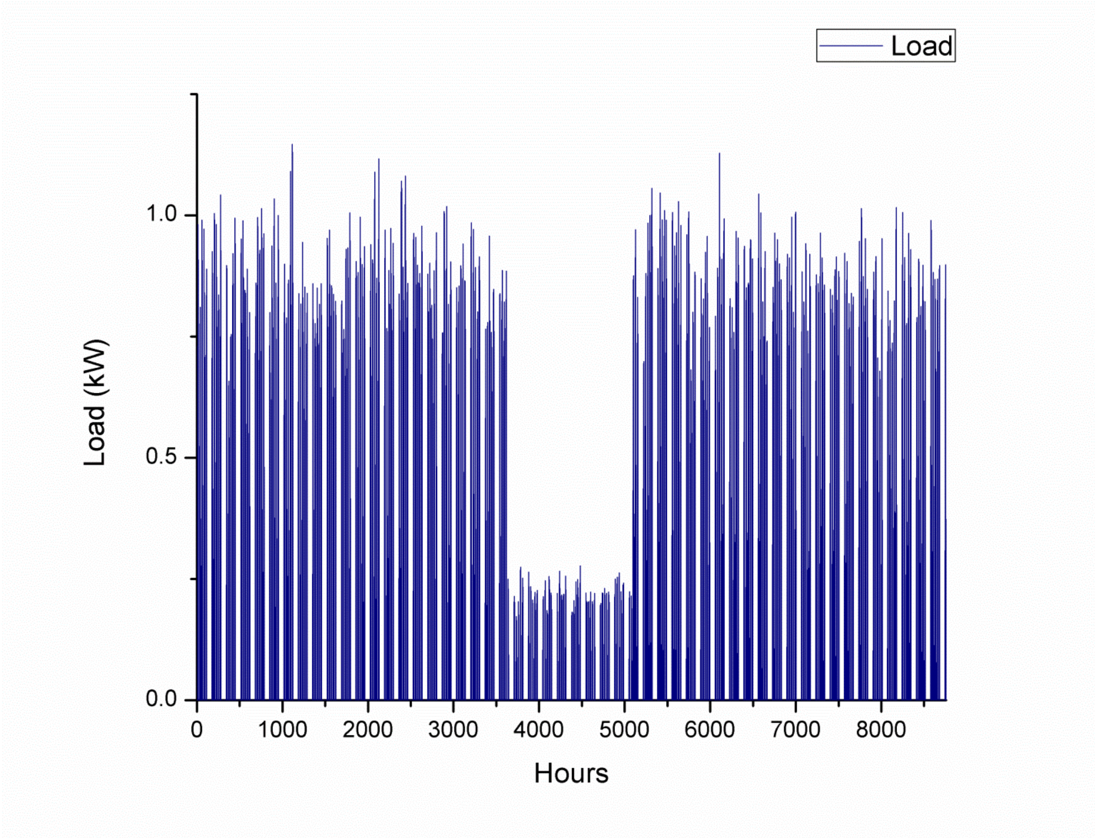


Fig. 2. Annual hourly load profile of CEE

3. Methodology

Solar radiation and wind speed time series data, measured for 2012 at the weather monitoring station at CEE, is used to assess the resource potential at the site. The solar radiation per minute data is imported in .txt format to calculate daily average irradiation and clearness index for each month, as shown in Fig.3. The annual average irradiation at the site is found to be 4.312 kWh/m^2/day with average clearness index (k_t) of 0.501.

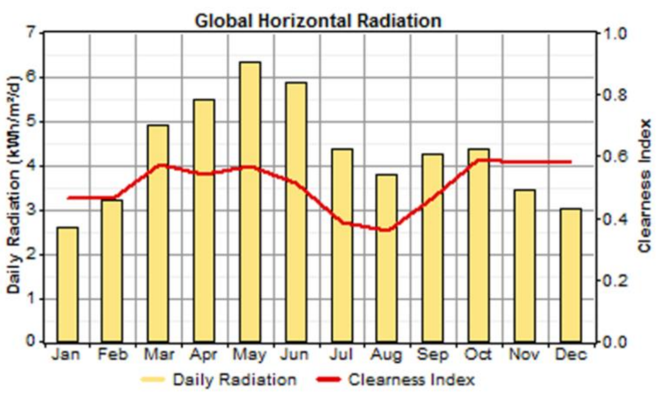


Fig. 3. Global solar radiation and clearness index at CEE, NIT Hamirpur

The wind speed data measured at 18.5 m height above ground is imported to HOMER in .txt format. The monthly average wind speed at the site is found to vary from 1.727 m/s to 2.532 m/s with annual average wind speed of 2.079 m/s. The hourly average wind resource of the site shows that there are various periods during the year when wind speeds are above 3 m/s (Fig. 4). The duration curve of wind speed is shown in Fig. 5 which depicts that the wind speed is more than 3 m/s for about 1247 hrs and from 4-10 m/s range for 304 hrs in a year. The wind power during these intervals is enough to generate electric power with a wind turbine having 2.5 m/s cut-in speed. The main objective of this study is to understand the contribution of different wind speeds even of short duration for power generation at locations with average low speeds but occasionally high wind speeds during the year so as to utilize the wind resource for small applications.

The Weibull probability density function [16] is given as

$$f_w(v)=\begin{cases}\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}e^{-\left(\frac{v}{c}\right)^k};v>0\\ 0;v\le 0\end{cases} \quad (1)$$

The Weibull shape and scale parameters are calculated as k = 2.29 and c = 2.35 m/s using eq.1. The Weibull shape parameter (k) describes the stability of wind speed while scale parameter (c) indicates wind speed magnitudes. Autocorrelation factor (typically 0.80 and 0.95) is the measure of hourly wind speed dependency on wind speeds in previous hours. The autocorrelation factor for this location is calculated as 0.692 which indicates wind speed is highly variable with time at this location.

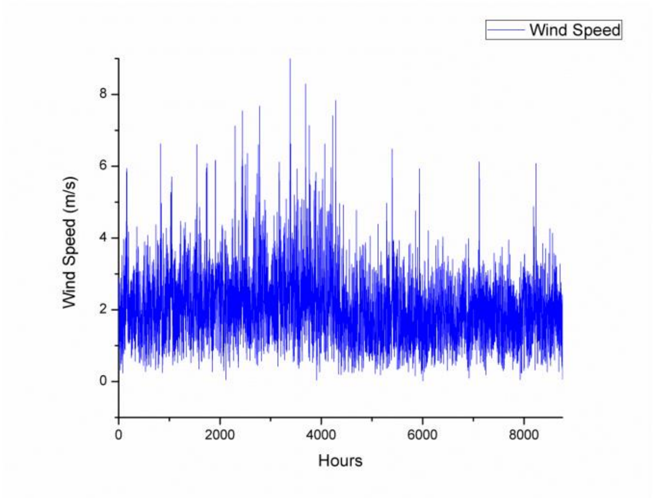


Fig. 4. Hourly average wind speed at CEE, NIT Hamirpur

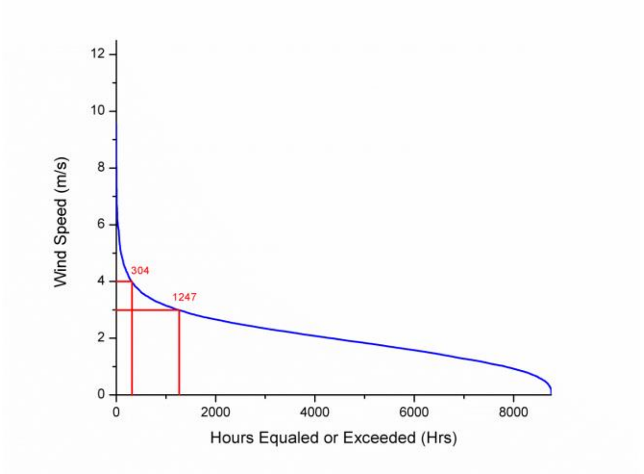


Fig. 5. Duration curve of wind speed at the site

The power generation by the PV array is simulated by Homer using eq. 2. This modeling equation also considers the solar cell temperature effect on the PV power production (eq. 3):

$$P_{pv} = P_{rpv} D_{pv} \left(\frac{\bar{G}_T}{\bar{G}_{Tstc}} \right) \left\{ 1 + \alpha_p (T_c - T_{stc}) \right\} \qquad (2)$$

where

$$T_c = \frac{T_a + (T_{cn} - T_{an}) \left(\frac{G_T}{G_{Tn}} \right) \left\{ 1 - \frac{\eta_{mp}(1 - \alpha_p T_{stc})}{\tau\alpha} \right\}}{1 + (T_{cn} - T_{an}) \left(\frac{G_T}{G_{Tn}} \right) \left\{ \frac{\eta_{mp}\alpha_p}{\tau\alpha} \right\}} \qquad (3)$$

The power extracted from the wind is given by

$$P_w = \frac{1}{2} c_p \rho A v^3 \qquad (4)$$

The eq. 4 is used to obtain the power curve of a wind turbine. The wind turbine is simulated by using its power curve, to calculate wind power production at hub height. The power curve of SNT- 50 as supplied by the manufacturer is shown in Fig. 6.

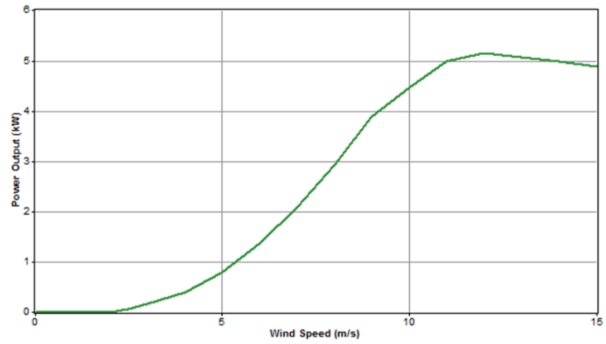


Fig. 6. Power curve of 5 kW_p wind turbine SNT-50

The results of simulation of 5 kWp wind turbine and 1 kWp PV experimental hybrid system are presented in the next section. Our aim is also to find suitable optimized system based on the solar and wind resource available at this location [17]. The hybrid system is optimized considering different sizes of PV array, wind turbine and battery bank as shown in Table 3.

Table 3. Various sizes and combinations considered for optimization

System	Combinations
Wind turbine	0, 1, 2, 3, 4, 5 (quantity in numbers)
PV array	0.5, 1, 2, 3, 4, 5 (size in kWp)
Battery bank	0, 1, 2, 3, 4, 5 (number of strings)
Converter	0.5, 1, 2, 3, 4, 5 (size in kWp)

The objective of the optimization is to minimize the net present cost (NPC) of the system with 0%, 5%, 10% and 20% capacity shortage and state of charge of battery bank should not be less than 80%. The formulated objective function with constraints is given by Eq. (5).

$$\min \sum NPC \qquad (5)$$

Constraints: 80%≤SOC≤100%

Capacity Shortage = 0%, 5%, 10% and 20%

The optimized system is evaluated for the given solar and wind resource and load for the location. It is important to optimize orientation and tilt angle for maximum solar radiation capture for the location. The various methods for determination of optimum tilt angles for the site of interest are described by Yadav and Chandel [18]. The annual optimum tilt angle of PV array for the site is determined as

27.1° which is used for the optimizing the hybrid system [19].

The cost of the system and excess electricity production are the governing factors in the optimization of a reliable stand-alone hybrid system. Therefore, the relation between capacity shortage, cost and excess electricity production for the optimum system configuration, is studied. The influence of capacity shortage on total net present cost and excess electricity production is shown in Fig.7 by the sensitivity analysis. The slope of net present cost and excess electricity is steep up to 5% and 10% capacity shortage respectively. Therefore, the maximum capacity shortage selected in this study is up to 10%.

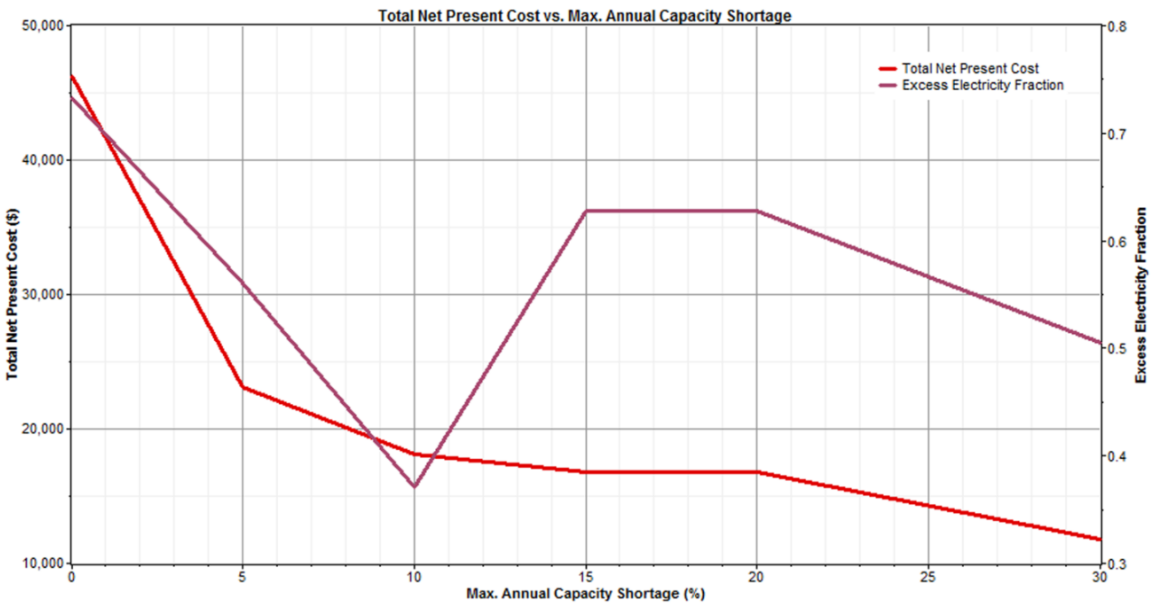


Fig. 7. Sensitivity analysis of maximum annual capacity shortage

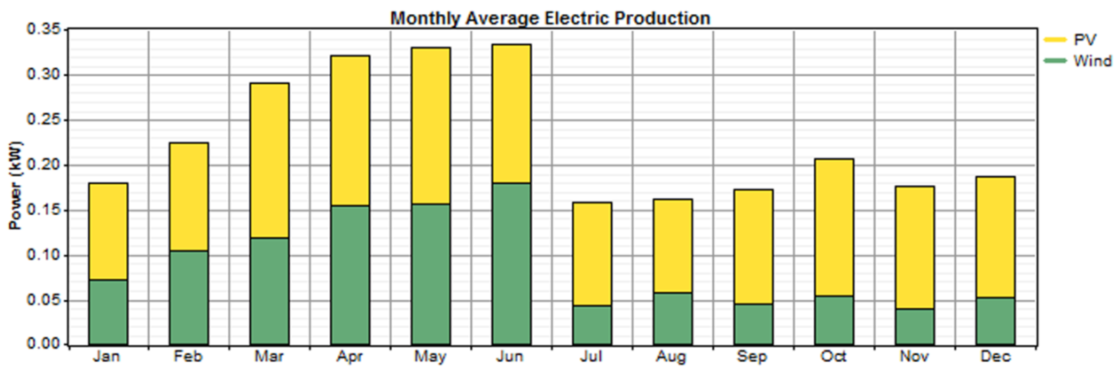


Fig. 8. Monthly average electricity production by solar -wind hybrid system

4. Results and Discussion

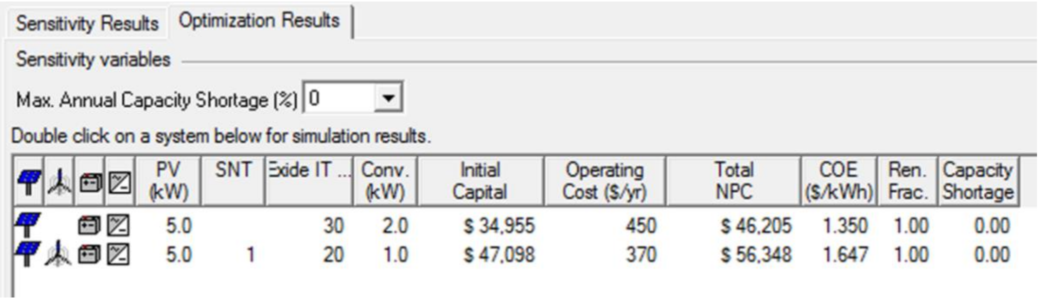
In this section, the results of existing and optimized hybrid system combinations are presented and discussed.

4.1. 6 kWp Solar -Wind hybrid System

Using the solar and wind resource of the location, the total electricity production during the year by the 6kWp hybrid system is obtained as 1996 kWh/yr in which 61% is of PV array (1214 kWh/yr) and 39% energy (782 kWh/yr) is estimated to be generated by wind turbine. The monthly average electricity production by wind turbine and PV array is shown in Fig. 8. The capacity shortage, net present cost (NPC) and levelized cost of energy (COE) of the system are 306 kWh/yr (22.3%), $30,734 and $1.156 1/kWh respectively.

4.2. *Optimum combinations of solar- wind hybrid systems*

The optimization results of the hybrid system as per load demand, available resources and economics for 0%, 5%, 10% and 20% capacity shortage are shown in Fig. 9(a, b, c & d). The results were calculated in 2376 simulations and are aligned in ascending order of net present cost.


Sensitivity Results | Optimization Results

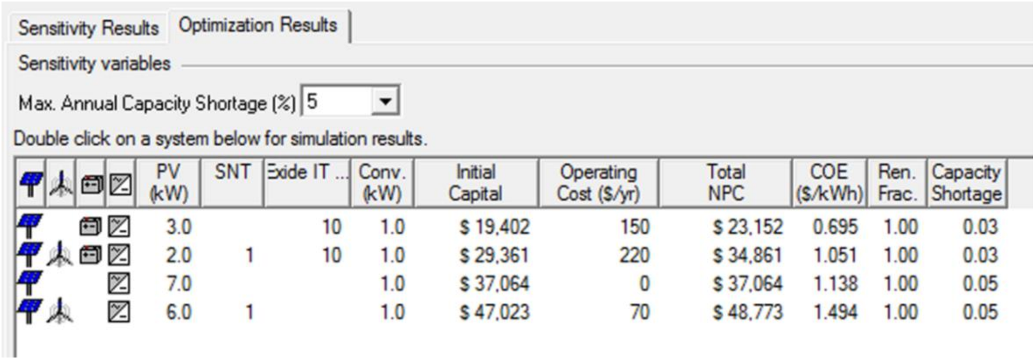
Sensitivity variables

Max. Annual Capacity Shortage (%) 0

Double click on a system below for simulation results.

PV (kW)	SNT	Exide IT ...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
5.0		30	2.0	$ 34,955	450	$ 46,205	1.350	1.00	0.00
5.0	1	20	1.0	$ 47,098	370	$ 56,348	1.647	1.00	0.00

Fig. 9a. Optimization results for 0% capacity shortage hybrid systems


Sensitivity Results | Optimization Results

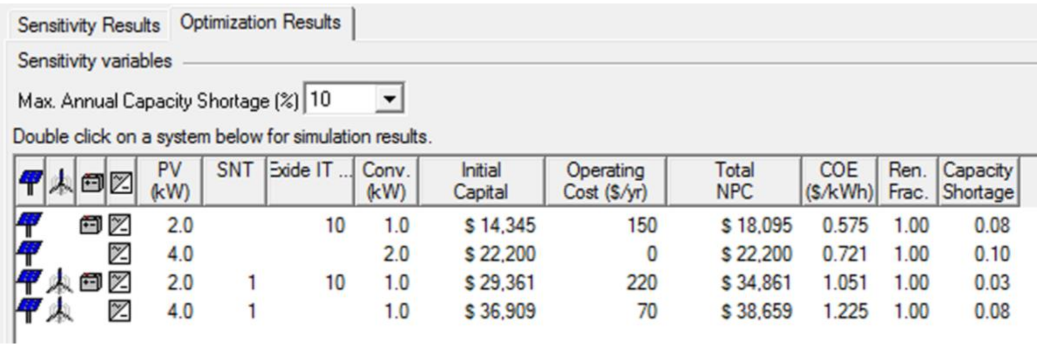
Sensitivity variables

Max. Annual Capacity Shortage (%) 5

Double click on a system below for simulation results.

PV (kW)	SNT	Exide IT ...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
3.0		10	1.0	$ 19,402	150	$ 23,152	0.695	1.00	0.03
2.0	1	10	1.0	$ 29,361	220	$ 34,861	1.051	1.00	0.03
7.0			1.0	$ 37,064	0	$ 37,064	1.138	1.00	0.05
6.0	1		1.0	$ 47,023	70	$ 48,773	1.494	1.00	0.05

Fig. 9b. Optimization results for 5% capacity shortage hybrid systems


Sensitivity Results | Optimization Results

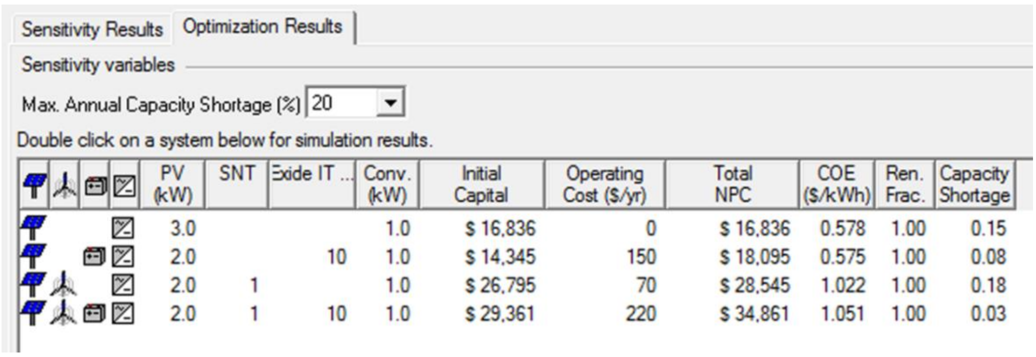
Sensitivity variables

Max. Annual Capacity Shortage (%) 10

Double click on a system below for simulation results.

PV (kW)	SNT	Exide IT ...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
2.0		10	1.0	$ 14,345	150	$ 18,095	0.575	1.00	0.08
4.0			2.0	$ 22,200	0	$ 22,200	0.721	1.00	0.10
2.0	1	10	1.0	$ 29,361	220	$ 34,861	1.051	1.00	0.03
4.0	1		1.0	$ 36,909	70	$ 38,659	1.225	1.00	0.08

Fig. 9c. Optimization results for 10% capacity shortage hybrid systems


Sensitivity Results | Optimization Results

Sensitivity variables

Max. Annual Capacity Shortage (%) 20

Double click on a system below for simulation results.

PV (kW)	SNT	Exide IT ...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
3.0			1.0	$ 16,836	0	$ 16,836	0.578	1.00	0.15
2.0		10	1.0	$ 14,345	150	$ 18,095	0.575	1.00	0.08
2.0	1		1.0	$ 26,795	70	$ 28,545	1.022	1.00	0.18
2.0	1	10	1.0	$ 29,361	220	$ 34,861	1.051	1.00	0.03

Fig. 9d. Optimization results for 20% capacity shortage hybrid systems

4.2.1. *Optimum combinations with 0% capacity shortage*

The best result for 0% capacity shortage is found to be a 5 kWp PV array, 2 kW converter, 3 parallel strings of battery bank (30 batteries) with net present cost (NPC) as $46,205 and cost of energy (COE) as $1.350 1/kWh. The total annual electric production of this system is obtained as 6,064 kWh/yr out of which 73.3% (4,444 kWh/yr) electricity, is in excess. The hourly electricity production of the best combination and excess electricity, are shown in Fig. 10.

The second best result in the same category is found to be 5 kWp solar array, a wind turbine of 5 kWp with 2 parallel strings battery bank and 1kWp converter having $56,348 NPC and COE to be $1.647 1/kWh. This system will produce total 6,846 kWh/yr electricity with 76.9% (5,261 kWh/yr) excess electricity. The hourly production from solar array and wind turbine is shown in Fig. 11.

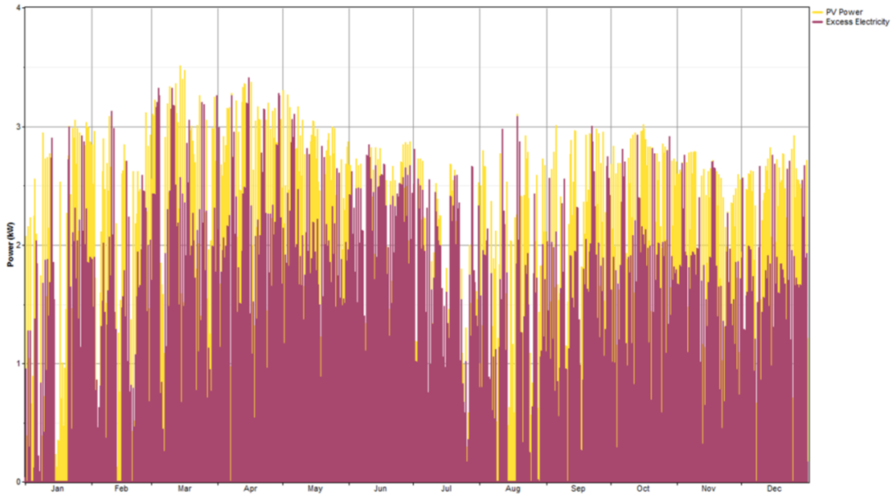


Fig. 10. Hourly PV power and excess electricity production by 5 kWp solar PV system with 0% capacity shortage

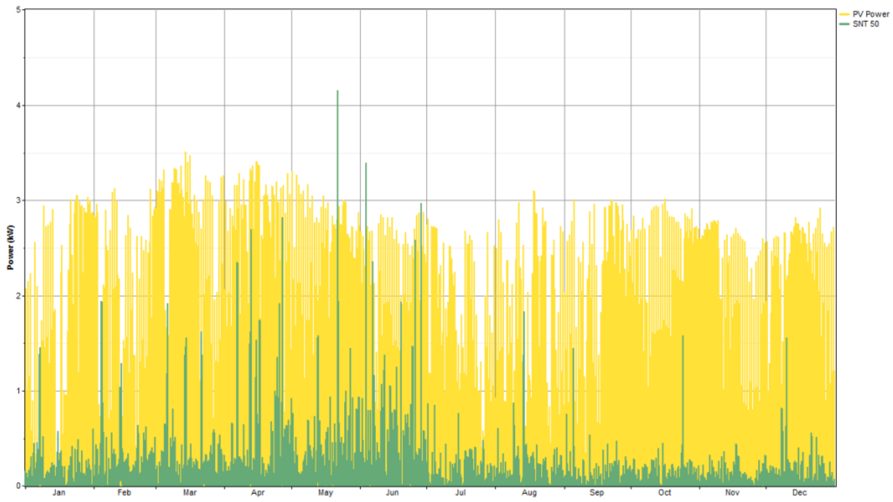


Fig. 11. Hourly power production by 5 kWp PV and 5 kWp wind system with 0% capacity shortage

The results show that the COE of both the systems, are high because of zero capacity shortage in entire year. The cost of energy can be reduced by either adding a diesel generator to the solar wind hybrid system or allowing nominal capacity shortage. The excess electricity production is very high for a 100% reliable system i.e. 0% capacity shortage, which can be utilized by serving deferrable load. A deferrable load is the load which can be deferred over time and can be served during the time of excess electricity production. The use of waste electricity in deferrable load doesn't affect the reliability of the system; moreover, the cost of energy will also reduce. Thus, it is advantageous to use deferrable load in reliable renewable energy systems.

4.2.2. Optimum combination with 5-10% capacity shortage

The best result for 5% maximum allowable capacity shortage, is obtained as 3 kW PV array with total number of 10 batteries (1 string) having NPC $23,152 and cost of energy $0.695 1/kWh with 56.1% (2041 kWh/yr) excess electricity production and 3% (35.5 kWh/yr) capacity shortage. For a maximum allowable capacity shortage of 10%, the best optimum combination comprises of 2 kWp PV array with 1 string of battery bank (total 10 nos. of batteries) with only 37.1% (899 kWh/yr) excess electricity and 8% (110 kWh/yr) capacity shortage. The NPC and COE of the system are $18,095 and $0.575 1/kWh. The monthly electrical power production results of this system, is shown in Fig. 12.

The excess power production by both the systems with 3% and 8% capacity shortage is shown in Fig. 13.

In order to utilize both solar and wind resource of the site, the optimized combination for this location, is found to be as one 5 kWp wind turbine and 2 kWp PV system with 1 string of 10 batteries. The COE of the system will be 1.051/kWh with 50.7% (1627 kWh/yr) excess electricity production with 3% capacity shortage as shown in Fig. 14.

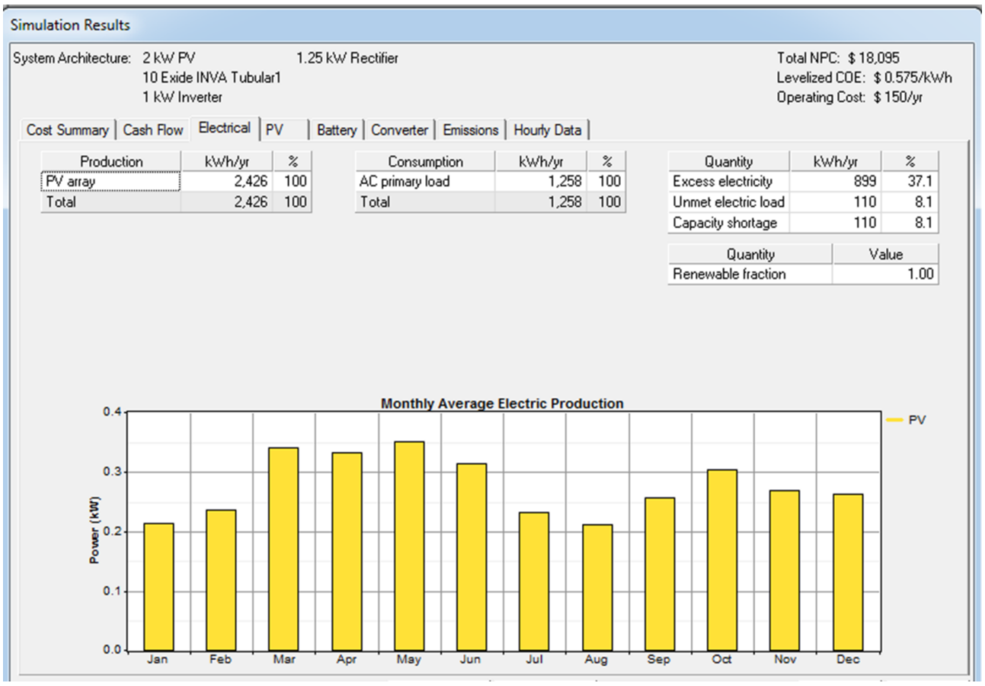


Fig. 12. Monthly Average Electricity production 2 kWp PV system

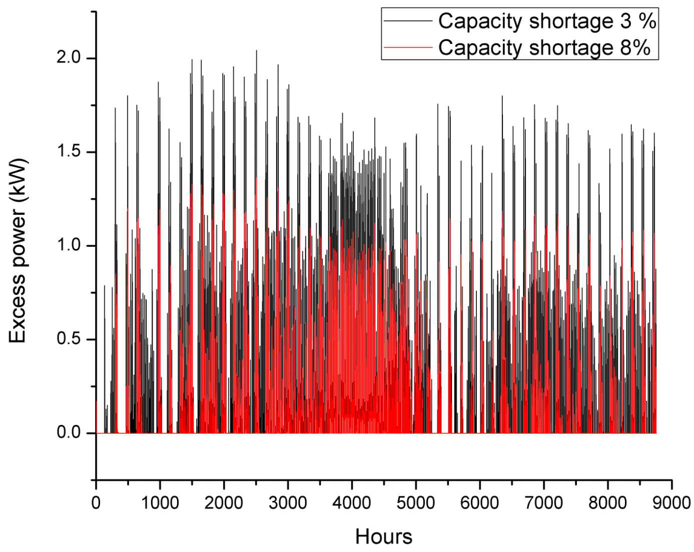


Fig. 13. Excess power production for 3% and 8% capacity shortage

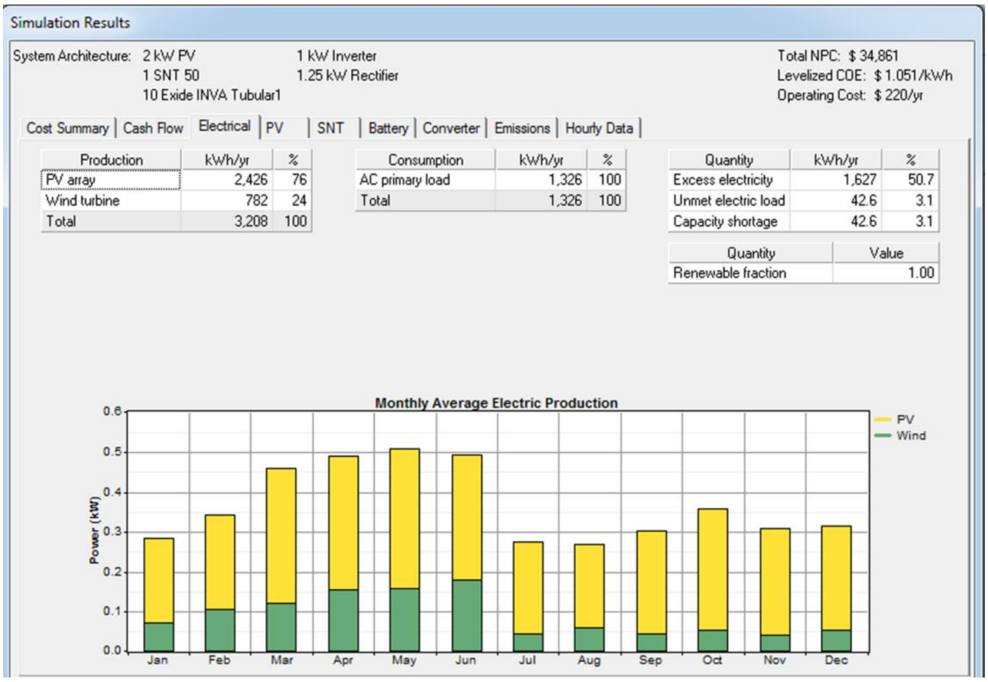


Fig. 14. Monthly average electricity production by 2 kWp solar PV array and a 5 kW wind turbine hybrid system

5. Conclusion

A 6 kWp Solar wind hybrid system installed on the roof top of an institutional building, is analyzed and optimized using HOMER software at different reliability levels in order to assess the feasibility of hybrid systems in Western Himalayan region. The system, is found to be effectively utilizing the available solar and wind source at the location and is able to meet the energy requirements of the day time use CEE office building.

The main conclusions are as follows:

1. The solar-wind hybrid systems will be reliable systems for residential/Institutional buildings both in urban and rural locations in the Western Himalayan region.

2. As a 100% reliable hybrid system is found to be oversized, costly and producing excess electricity, a system with deferrable load, acceptable capacity shortage and optimized depth of discharge will be more suitable for such locations..

3. A diesel generator can also be integrated in a solar-wind-battery hybrid system to avoid over-sizing and enhancing reliability of the system.

4. The optimum system for this location, is found to be a 2 kWp solar PV array, 5 kWp wind turbine and a string of ten 12V batteries with total NPC as $34,861 and COE as $1.051 1/kWh respectively. In comparison with the existing system, the cost of optimum wind solar hybrid system is slightly higher but the capacity shortage drops to 3.1% from 22.3% therefore an addition of 1 kWp Solar PV system can be added to the existing system.

5. A 2 kWp solar photovoltaic system using only solar resource is found to be more cost effective than the 6 kWp wind- solar hybrid system for this site but utilization of wind resource is of great importance in the remote off grid rural locations in the complex Himalayan terrain where sufficient wind resource is also available.

6. HOMER is most widely used software for quick analysis of hybrid systems but it does not consider depth of discharge (DOD) of battery bank in the optimization of hybrid system which needs to be included as both life and size of battery bank decreases with the increase in DOD. The software doesn't provide flexibility in selecting optimization technique relevant to a particular study and allows only single objective function for minimizing the NPC as such the multi-objective problems cannot be formulated. These aspects needs to be considered in further improving the HOMER.

Further follow up studies are required to be carried for the design and development of reliable hybrid systems for the Himalayan region including biomass / diesel generator for enhancing the reliability of a hybrid system for remote and inaccessible locations.

References

[1] S. M. Shaahid, and M. A. Elhadidy, “Economic analysis of hybrid photovoltaic-diesel-battery power systems for residential loads in hot regions-a step to clean future”, Renewable and Sustainable Energy Reviews, Vol. 12, pp. 488-503, 2008.

[2] K. Hasan, K. Fatima, and M. S. Mahmood, “Feasibility of hybrid power generation over wind and solar standalone system”, The 5th International Power Engineering and Optimization Conference, Shah Alam, Selangor, Malaysia, pp. 139-143, 6-7 June 2011.

[3] G. Vuc, I. Borlea, C. Barbulescu, O. Prostean, D. Jigoria-Oprea, and L. Neaga, "Optimal energy mix for a grid connected hybrid wind – photovoltaic generation system", 3rd IEEE International Symposium on Exploitation of Renewable Energy Sources, Subotica, Serbia, pp. 129-132, March 11-12, 2011.

[4] H. Abdolrahimi, and H. K. Karegar, "Optimization and sensitivity analysis of a hybrid system for a reliable load supply in Kish_Iran", International Journal of Advanced Renewable Energy Research, Vol. 1, No. 4, pp. 217-225, 2012.

[5] D. K. Lal, B. B. Dash, and A. K. Akella, "Optimization of PV/wind/micro-hydro/diesel hybrid power system in HOMER for the study area", International Journal on Electrical Engineering and Informatics, Vol. 3, No. 3, pp. 307-325, 2011.

[6] S. Lal, and A. Raturi, "Techno-economic analysis of a hybrid mini-grid system for Fiji Islands", International Journal of Energy and Environmental Engineering, pp. 1-10, 2012.

[7] A. H. Mondal, and M. Denich, "Hybrid systems for decentralized power generation in Bangladesh", Energy for Sustainable Development, Vol. 14, pp. 48–55, 2010.

[8] A. Shiroudi, R. Rashidi, G. B. Gharehpetian, S. A. Mousavifar, and A. A. Foroud, "Case study: simulation and optimization of photovoltaic-wind-battery hybrid energy system in Taleghan-Iran using homer software", Journal of Renewable and Sustainable Energy, Vol. 4, pp. 1-11, 2012.

[9] M. S. Alam, and D. W. Gao, "Modelling and analysis of a wind/PV/fuel cell hybrid power system in HOMER", Second IEEE Conference on Industrial Electronics and Applications, pp. 1594-1599, 2007.

[10] J. B. Fulzele, and S. Dutt, "Optimium planning of hybrid renewable energy system using HOMER", International Journal of Electrical and Computer Engineering, Vol. 2, No. 1, pp. 68-74, February 2012.

[11] N. Lopez, and J. F. Espiritu, "An approach to hybrid power systems integration considering different renewable energy technologies", Procedia Computer Science, Vol. 6, pp. 463–468, 2011.

[12] V. Reddy, and A. Raturi, "Optimization and sensitivity analysis of a PV/wind/diesel hybrid system for a rural community in the Pacific", Applied Solar Energy Vol. 46, No. 2, pp. 152-156, 2010.

[13] A. Zaman, M. A. Rahman, and S. Islam, "Design of a hybrid power system for rural area", Journal Basic Science and Technology, Vol. 1, No. 2, pp. 1-4, 2012.

[14] B. Dursun, C. Gokcol, I. Umut, A. Ucar, and S. Kocabey, "Techno-Economic Evaluation of a Hybrid PV—Wind Power Generation System", International Journal of Green Energy, Vol. 10, pp. 117–136, 2013.

[15] F. A. Farret and M. G. Simoes, Integration of Alternative Sources of Energy, John Wiley & Sons Inc., 2006, ch. 15.

[16] B. S. Borowy, and Z. M. Salameh, "Methodology for Optimally Sizing the Combination of a Battery Bank and PV Array in a Wind/PV Hybrid System", IEEE Transactions on Energy Conversion, Vol. 11, No. 2, pp. 367-375, 1996.

[17] S. Sinha and S. S. Chandel, "Pre-feasibility analysis of solar-wind hybrid system potential in a complex hilly terrain", International Journal of Emerging Technology and Advanced Engineering , Vol.3, Special Issue 3, pp. 277-282, 2013.

[18] A. K. Yadav, and S. S. Chandel, "Tilt angle optimization to maximize incident solar radiation: A review", Renewable and Sustainable Energy Reviews, Vol. 23, pp. 503-513, 2013.

[19] P. Yadav, and S. S. Chandel, "Optimal Slope Angles for Solar Photovoltaic Panels for Maximum Solar Energy Gain", International Journal of Sustainable Development and Green Economics, Vol. 2, No. 1, pp. 85-89, 2013.

Nomenclature

T_c	PV cell Temperature (°C)	D_{pv}	Derating factor of PV array (77%)
T_{cn}	Nominal operating cell temperature (47°C)	η_{mp}	Maximum power point efficiency under STC (13%)
T_{an}	Nominal ambient temperature (20°C)	α_p	Temperature coefficient of power (-0.48%/°C)
T_{stc}	Cell Temperature under STC (25°C)	$\tau\alpha$	Product of solar transmittance and absorptance (0.9)
G_T	Solar radiation at the tilted surface	c_p	Coefficient of power from wind turbine
G_{Tn}	Solar radiation at NOCT (0.8 kW/m^2)	v	Wind speed (m/s)
G_{Tstc}	Solar radiation at STC (1kW/m^2)	A	Cross-sectional area of wind turbine
P_{pv}	Output of PV array	ρ	Air density
P_{rpv}	Rated capacity of PV array	$	U.S. Dollar