A Solar-Wind Hybrid Renewable Energy System

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***Abstract*:** Solar-Wind Hybrid Energy Systems (SWHES) are the future for rural electrification in India where grid power access is poor. A case study of Solar-Wind Hybrid Energy System (SWHES) is presented here for electrifying three households in Vighakot village in Gujarat, India. The details of design and analysis is reported such that the installed SWHES can produce continuous power without any fluctuation throughout the day. The methodology includes collection of wind speed and solar irradiation data for the selected site and estimation of the demand load of the household in terms of daily usage. Using this data, the sizing and specifications of the system components are made, which are then used to test the system operation and establish its capability to meet the energy demand. HOMER, an open-source software is used for the system simulations and parametric optimization. The simulation results also displayed power variation of both wind and solar PV in the hybrid system for an entire year. The wind turbine generates a higher share of 75.6% energy in the system and PV panel generates a lower share of 24.4%. Analysis reported in this article will serve as a ready reference for energy consultants planning to set up SWHES for rural electrification.

***Index Terms*-- Solar-Wind Hybrid Energy System (SWHES), HOMER, Solar Irradiation, Grid Independent Power generation.**

I. INTRODUCTION

IN India which has the second most population worldwide, 65.5% of total population reside in rural areas with inconsistent access to electricity. Majority of the world's electricity is presently produced using expensive, quickly depleting fossil fuels like coal, oil, and natural gas, which also produce greenhouse gases. Thus, the share of renewable energy for electricity generation particularly in rural areas is increasing rapidly in India [1]. This is because in most part of rural India one of the renewable sources such as solar, wind or hydro are in abundance.

Currently among renewable sources, wind systems and PV systems are deployed on a wider scale. These independent systems are however unable to produce a continuous source of energy as they are seasonal. Wind standalone systems cannot meet the load demands because of fluctuations in wind speed throughout the year and Solar PV systems are not able to provide reliable power during night. Hybrid Renewable Energy System (HRES) is an integration of two or more renewable energy source to produce a more dependable and high-quality power supply that is not dependent on the national grid [2–6]. Hybrid systems, incorporating two or more renewable energy sources coupled with an energy storage system and an algorithm to operate the system is considered as a promising technology for power generation in rural areas [3].

Among all renewable energy sources, the integration of solar and wind energy sources is considered most effective due to their complementary nature hence providing a reliable and cost-effective option for rural electrification. A key advantage of this system is that it can deliver continuous power throughout the day without interruption with the incorporation of an energy storage device which stores excess energy and uses it in case when there is no power generation from the both the units [4].

II. LITERATURE REVIEW

There are different methodologies adopted by different authors for designing and simulating solar-wind hybrid energy systems (SWHES). A study by Ambia et al. [2] focused on designing a solar-wind HRES which can be implemented for rural areas to obtain power from national grid without fluctuation and for off grid areas. The authors suggested that the proposed system could be enhanced by introducing multi-agent control and optimal sizing of the whole system. They also created an algorithm which was used in the charge controller that decides the power flow in the whole hybrid system. This algorithm ensures that wind and solar energy are used to the fullest extent possible. The authors however did not report system level simulation which would show the feasibility of using this hybrid system for power generation.

Ahmed et al. [5] presented a study dealing with the control and simulation of a grid-connected hybrid PV system. The control techniques for various system components were suggested along with models. With various input parameters (wind speed and solar radiation), the simulation showed voltages and currents across various system components. The design of the system's power electronic components was based on the simulation findings. They also claimed that with a fixed rotational speed of the turbine, the DC voltage remains practically constant at high wind speeds. The authors however did not consider inputs from a specific location to test the hybrid system, instead varied the inputs to examine the performance of the designed system.

Bhandari et al. [6] highlighted the increasing advantages of using HRES for remote and rural electrification due to the decline in costs of solar PV and wind turbines in recent years.

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A short mathematical model of various generators and battery bank was presented along with a review of optimization methods and design criteria for the HRES. Methods related to the hybrid system modelling were discussed by the author, but no simulation was reported.

Tina and Gagliano [7] studied the impact of using tracking system on energy performance of a hybrid system. They used a fixed tilt angle, a 1-axis tracking system, and a 2-axis tracking system to analyze a probabilistic model of a solar-wind hybrid system. It was discovered that 2-axis tracking system outperforms 1-axis tracker in terms of monthly electricity generation. Ssenyimba et al. [8] conducted a case study on the design of a solar-wind HRES for agricultural irrigation. This research demonstrated the sizing of individual components of an HRES like solar PV module, wind generator and battery bank. The author had designed a hybrid system for irrigation purposes not for generation of power for household.

Performance of hybrid solar-wind renewable energy systems can be effectively improved by making proper use of their operating characteristics. Procedure for sizing of the solar-wind hybrid energy system (SWHES) components is depicted in the works reported by Ambia et al. [2] and Ssenyimba et al. [8]. However, a complete study that includes design and simulation of a hybrid system and testing its performance throughout the year on a selected site is not available in literature. Therefore, the present research is focused on carrying out a resource assessment on a potential site in India and use those parameters as inputs to design a SWHES. HOMER which is a system simulation software helps in designing the proposed system architecture and carry out a system level simulation to estimate the systems power generation capability for a year. This helps in identifying whether deploying the hybrid system at the selected site can meet the load demand and is not intermittent. The simulation results also show a DMapp from which the variability of energy generation can be seen. This research investigates the feasibility of utilizing wind and solar energy for electrifying three households located near Vighakot village in Gujarat, India.

The present article is divided as follows: Section 3 gives an overview on the solar and wind energy potential in India. Section 4 covers the design methodology for the hybrid system. Section 5 discusses in detail the case study which includes resource assessment, system component sizing and simulation along with the results and discussion. The concluding remarks of the study are highlighted in Section 6.

III. SOLAR AND WIND ENERGY POTENTIAL IN INDIA

The total potential of renewable energy in India as of 2020 is 10,97,465 MW. Out of this, solar power potential is leading with 7,48,990 MW and Wind Power potential is 3,02,251 MW at 100 m hub height [9]. The distribution of India's potential for renewable energy is shown in Figure 1.

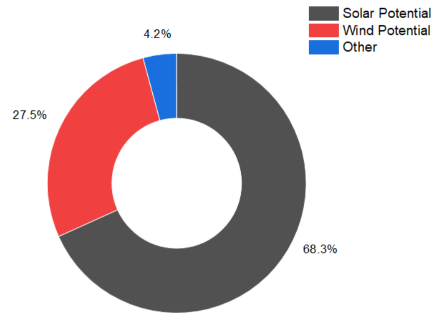


Fig. 1. Estimated Potential of Renewable Energy as of 2020.

A. Solar Potential

India is provided with a vast solar energy which is equivalent to about 5000 trillion kWh per year. Most parts of India receive 250 to 200 sunny days/year and provides a daily average of 4-7 kWh per sq. m per day which is almost equivalent to the average daily consumption per household in India (10 kWh / household) [10]. Solar PV power can be harnessed effectively hence providing huge scalability in India. Solar energy provides us with the ability to harness power in a decentralized manner which is off-grid hence independent households can have their own electricity producing system at their homes. Off-Grid decentralized and low temperature applications are viewed as beneficial for rural electrification in India.

With the premise that 3% of India's waste land area will be covered by solar panels, the National Institute of Solar Energy (NISE) estimated the country's solar potential to be at 748 GW. The Government of India's National Solar Mission (NSM) aims to develop 100 GW of grid-connected solar PV power plants by 2022. India has surpassed Italy to take fifth place globally in solar PV installation. As shown in Fig. 2, the solar power capacity has expanded more than six times in five years, from 6800 MW in 2016 to 40100 MW in 2021[10].

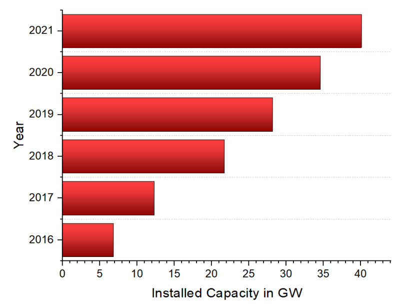


Fig. 2. Evolution of installed solar capacity.

B. Wind Potential

India ranked fourth in global position in wind energy capacity as of 2020 with a total of 39250 MW. India has the second-highest wind capacity in Asia and generated roughly 60.149 billion units between 2020 and 2021. India has the third (1500 MW - Muppandal wind farm in Tamil Nadu) and fourth (1064 MW - Jaisalmer Wind Park in Rajasthan) largest onshore wind farms in the world. To evaluate the country's wind resources, the Indian government, through the National Institute of Wind Energy (NIWE), has installed more than 800 wind monitoring stations. Wind potential maps have been created at altitudes of 50, 80, 100, and 120 meters above ground level. India has a capacity for 695500 MW at 120 meters above the ground and 302000 MW at 100 meters, according to a recent evaluation.

Seven states in India showed wind potential of more than 44000 MW at 100m and 74900 MW at 120m. Out of these 7 states Gujarat has highest wind potential with 84430 MW at 100m and 142560 MW at 120m followed by Rajasthan with 18770 MW at 100m and 127750 MW at 120m [11]. The wind energy industry currently accounts for the majority of India's total renewable energy capacity, or 41.5%, with an installed capacity of 39248 MW. Evolution of installed wind capacity in India from 2016 is shown in Fig. 3.

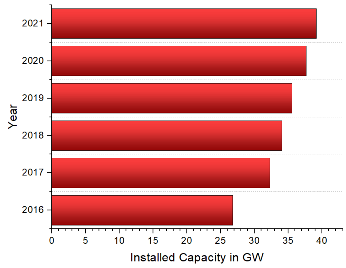


Fig. 3. Evolution of installed wind capacity.

IV. METHODOLOGY

The objective of this research is to design and optimize a SWHES in a rural location in India to supply un-interrupted power to three households. In this direction, first, the wind speed and solar irradiation data for the selected site is collected and assessed to evaluate the monthly averaged wind speed and solar irradiation. The power needs of a rural household are calculated based on daily usage to estimate the load demand of the system. From the above two sets of data, the system components are sized. Once sizing is completed, the next step involved modelling of the hybrid system and simulations to predict the influence of parameters on the system performance towards possible improvements in the system design. Fig. 4 summarizes the whole process flow.

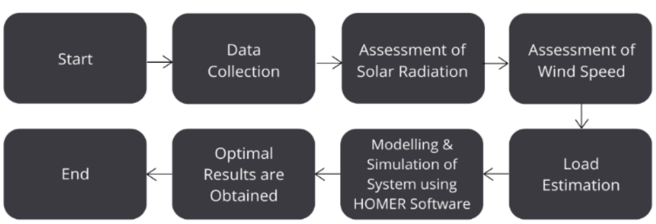


Fig. 4. Process flow diagram for research.

V. DESIGN OF HYBRID SOLAR-WIND ENERGY SYSTEM

The bock diagram of the Solar-Wind Hybrid Energy System (SWHES) proposed here is shown in Fig. 5. Through the use of a controller, the wind turbine and solar panel combine to charge a battery. The charge controller helps in regulating the charging process before it is stored in the storage medium. An Inverter helps in converting DC output voltage of the storage into AC voltage for AC loads. If one of the systems failed to generate power; for example, if the PV system is unable to generate power at night, then the Wind system will supply the power which gets stored in the battery bank hence this system maintains the continuity of power supply. The load monitoring is done by using a specific algorithm which is coded into the charge controller.

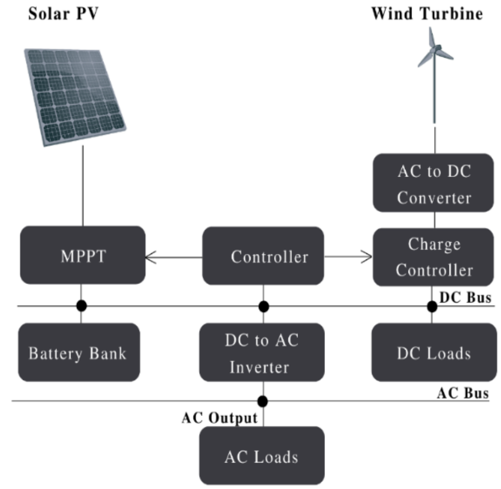


Fig. 5. SWHES Block Diagram.

An off-grid hybrid system's block diagram is shown in Fig. 6. These systems are very useful to be implemented in rural areas. In off grid system, wind turbine and PV panels are the main energy generators. To deliver both DC and AC loads, the system additionally contains a controller to manage the load and battery [2].

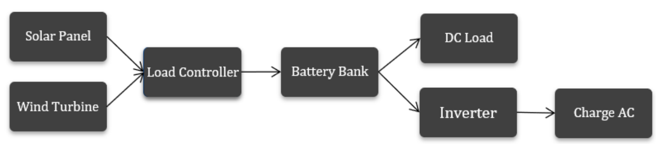


Fig. 6. Block diagram of Off-Grid Hybrid System.

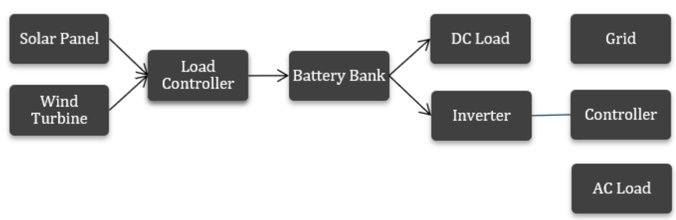


Fig. 7. Block diagram of On-Grid Hybrid System.

An on-grid hybrid system's block diagram is shown in Fig. 7. With batteries, a regulator, a wind turbine, and solar panels, this system is similar to an off-grid setup. Only difference here is that the whole system is connected to the national grid for power generation in cases where solar and wind are unavailable to produce electricity. Another controller receives input from the grid, and that controller's output is linked to the AC loads. The availability of the output from the inverter determines which of the two inputs—one from the inverter and one from the grid—the controller chooses. The controller selects the grid line and then transmit power to the load if the inverter is unable to produce an output [2].

A. *Site Selection and Resource Assessment*

A survey conducted by the Indian Ministry of New and Renewable Energy served as the basis for site selection. State of Gujarat State has a Wind potential with 84.43 GW at 100m height. Gujarat is also placed at number 5 in terms of Solar potential with 2,654 MW [18]. Hence Gujarat is an ideal location to set up the Solar-Wind Hybrid System. Since the research is focused on electrification of rural areas, hence Vighakot village near Kutch district of Gujarat is chosen as the site for deployment. Site Coordinates are shown in Table I.

TABLE I
Coordinates of Vighakot Village.

	Latitude	Longitude
Site Coordinates	24.21534102° N	69.19548725° E

I. Wind Speed Assessment:

Wind data of Vighakot site from January 2020 to December 2020 is used for analysis. The data for this period is collected from NASA Prediction Worldwide Energy Resource (POWER) database. The Annual average wind speed at 50m height is estimated to be 6.15 m/s. In Fig. 9, the monthly fluctuation in wind speed is depicted graphically. From the figure it can be noted that higher wind speeds occur during April to September with wind speed above 6.00 m/s while lower wind speeds occur from October to December and during the first three months of the year having wind speed less than 6 m/s. Hence, the deployment of wind turbine at this location is ideal.

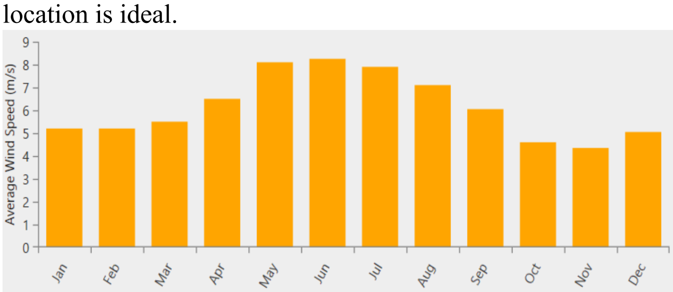


Fig. 9. Monthly Average Wind Speed Pattern in Vighakot.

II. Solar Radiation Assessment:

Solar data of Vighakot site from January 2020 to December 2020 is used for this analysis. The data for this period is collected from National Renewable Energy Laboratory (NREL) database. The Annual average solar radiation is found to be 5.50 kWh/m^2/day. In Fig. 10, the monthly fluctuation in solar radiaion is depicted graphically. It can be seen from the figure that higher solar radiation occurs during March to June and other months have radiation less than 6.00 kWh/m^2/day. The clearness index (K_t) ranges from 0.47 to 0.64 indicating that all the months are sunny, and no month is very cloudy. A clearness index of 0.25 indicates a very cloudy month, but Vighakot does not display this value. Hence the site is ideal for solar PV deployment.

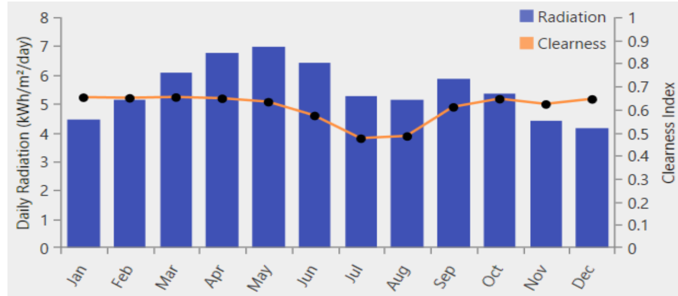
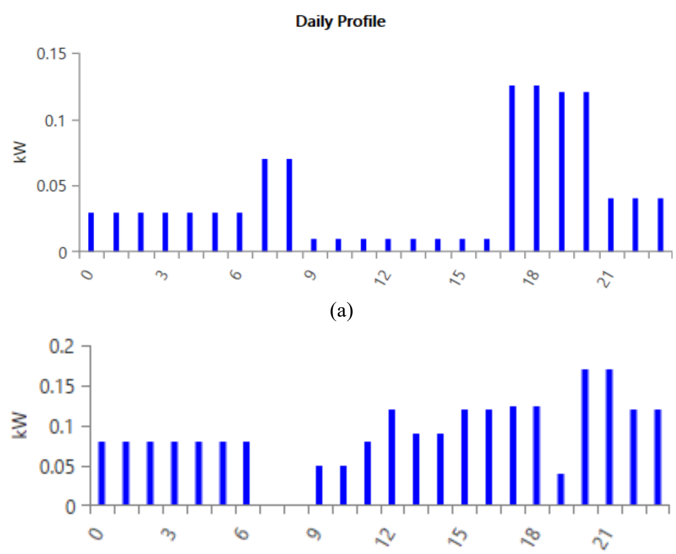


Fig. 10. Monthly Average Solar Radiation Pattern in Vighakot.

III. Load Estimation:

Before designing the Hybrid system, it is vital to determine the load demand from the system. The daily load profile indicating load vs operation hour of the day of a household is shown in Fig. 11 (a). The total energy demand expected from the whole system during a weekday was determined to be 1.09 kWh. The daily load profile for a weekend is shown in Fig. 11(b), and it was determined that the system's overall weekend energy consumption was 2.15 kWh. Considering 30 days in a month with 22 weekdays and 8 weekends the monthly energy demand of one household is estimated to be about 41.18 kWh which is in the range of the energy consumption (39.9 kWh) of an average rural household in India [19]. So, for designing of the system, weekend power demand is considered to be higher. In order to ensure that the system is always effective for producing energy, each of the two energy generators is designed to be able to provide a minimum quantity of power more than the peak demand at any given moment. A detailed split of load and energy calculation for a single household is summarized in Table II. This load data is used by HOMER model for system design and analysis.



(b)

Fig. 11. Daily load profile in the household during (a) weekday and (b) weekend.

TABLE II
Estimated energy demand of various appliances used in the household during a weekday and during a weekend.

Appliance	Quantity	Power Rating (W)	Total Load Demand (W)	Hours of Operation (hrs)	Daily Energy Demand (Wh)
During a Weekday					
Fan	2.00	40.00	80.00	8.00	640.00
Lighting	4.00	10.00	40.00	6.00	240.00
Television	1.00	50.00	50.00	4.00	200.00
Other accessories	2.00	2.50	5.00	2.00	10.00
Total			175.00		1090.00
During a Weekend					
Fan	2.00	40.00	80.00	17.00	1360.00
Lighting	4.00	10.00	40.00	12.00	480.00
Television	1.00	50.00	50.00	6.00	300.00
Other accessories	2.00	2.50	5.00	2.00	10.00
Total			175.00		2150.00

B. System Component Details

The SWHES comprises of various components which include Solar and Wind Generators, Charge Controller, Battery Bank, Inverters and AC to DC Converters.

I. SOLAR PV SYSTEM:

A photovoltaic matrix is created by connecting PV cells in a series-parallel pattern [15]. Fig. 12 represents a modelled circuit with single ideal diode. The following are the mathematical expressions for photocurrent and reverse saturation current:

$$I_{rs}(t) = I_{or}\left(\frac{T(t)}{T_{ref}}\right)^3 \exp\left(\frac{q\left(E_{g0}(1/T_r)-1/T(t)\right)}{KT(t)}\right) \quad (2)$$

$$I_{ph}(t) = (I_{sc} + K_l T(t) - T_r) \times \lambda(t)/1000 \quad (3)$$

Here, I_{or} represents inverse saturation current, Ego is band gap energy, I_{sc} represents SC current and λ represents insolation in mW/cm^2 [20].
Solar cell conversion efficiency is represented as:

$$\eta_c = \frac{P_{max}}{P_{in}} = \frac{I_{max}\times V_{max}}{I(t)\times A_c} \quad (4)$$

Here, I_{max} and V_{max} are the current and voltage for maximum power and $I(t)$ and A_c are the solar intensity and area of solar cell respectively [21].

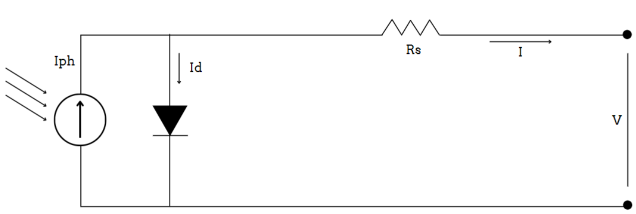


Fig. 12. PV model with a single diode.

II. WIND ENERGY CONVERSION SYSTEM:

The wind energy conversion system comprises of a wind turbine, PMSG and wind MPPT mechanism. Pitch angle controller limits the speed of wind turbine in the cases where wind speed exceeds more than cut out speed [22]. Electricity generated from a wind turbine is based on the amount of wind speed available in the region where the turbine is placed as well as the mechanical coupling of the rotors to an electric generator. Equation 6 illustrates the expression for mechanical power output from wind turbine.

$$P_{WT}(t) = \frac{1}{2} C_p(\lambda,\beta)\rho_a A v^3 \quad (6)$$

The input-output energy transformation for wind power and electric power is depicted in Fig. 13.

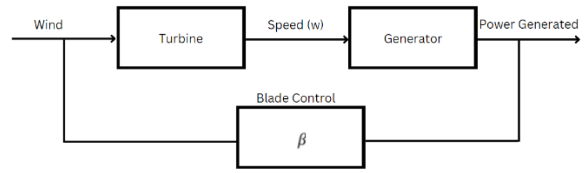


Fig. 13. Energy conversion plan

The wind turbine's output power and its limitations are shown in Equation 7. If the load is lower than the power rating, the turbine will run with a variable rotor speed. With wind speeds exceeding the rated value, the turbine will continue to operate at a constant output power. Wind turbine stops operating if wind speed is less than the nominal speed $v < v_i$ and $v < v_c$.

$$P_w^{av}(t) = \begin{cases} 0 \text{ if } v < v_i \\ \frac{1}{2} C_p(\lambda,\beta)\rho_a A v^3(t) \text{ if } v_i \le v \le v_r \\ P_w^r \text{ if } v_r < v < v_c \\ 0 \text{ if } v > v_c \end{cases} \quad (7)$$

III. CHARGE CONTROLLER:

The primary duty is to regulate whether a source should be active or inactive. When a PV panel is connected to a load, the output usually does not stay constant since the sun irradiation varies during the day. Therefore, backup systems are used to supply the need for electricity under such circumstances. These charge controllers monitor when the battery should be charged and when it should be disconnected from the power supply. In addition to powering the load, it also charges the battery simultaneously. The controller contains several protections, including the automatic dump load function, pole confusion protection, over-charge protection, and SC protection. The controllers assist in adjusting power according to load requirements. It draws electricity from the battery bank and supplies it to the load when no power is being drawn. Between the DC bus and the wind/solar module is the charge controller. To determine when to charge or when to disconnect, they utilize set point as a reference [2].

The controller can have an inbuilt algorithm which decides the controls. Ambia et al. [2] devised an algorithm based on the requirements of an ideal hybrid system. In the algorithm, the wind turbine is given priority. When the wind energy exceeds cut in velocity then the battery bank 1 will be charged hence enabling DC supply for DC loads or AC supply using an inverter for AC loads. But if the wind energy is less than the cut in velocity then the controller will decide to use the solar module. The controller determines if the solar radiation is sufficient to provide the needed energy. If not, then the controller chooses to utilize the power grid system and determines if it is or is not available. If it is available, it will draw power from the grid; otherwise, the controller will determine if Battery Bank 1 has enough charge to generate electricity. If the battery bank 1 charge is sufficient enough, then the power will be taken from it else it will be taken from battery bank 2 which is charged by the solar panel. The system guarantees maximal wind and solar energy usage without a connection to the grid by employing this algorithm.

IV. *Battery Energy Storage System:*

The Battery Energy Storage System is used to aid the hybrid system in ensuring smooth and stable functioning as well as keeping a steady voltage during power generation and consumption mismatches [23]. An electric circuit which is used to describe the equivalent battery model is represented in Fig. 14 and consists of an idealized voltage source with an internal series resistance.

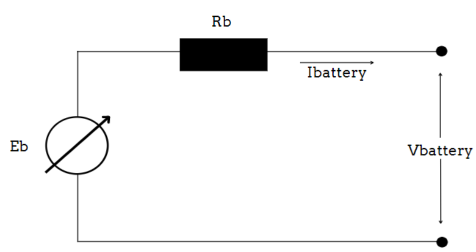


Fig. 14. Equivalent Battery Circuit.

To prevent battery failure certain battery conditions, need to be observed as shown below [16].

a. State of charge, SOC: This represents the battery's current capacity as a share of its maximum capacity. The change in battery capacity over time is calculated using current integration.

$$\text{SOC}\,(t) = \text{SOC}\,(t-1) * (1-\sigma) + \left[E_g(t) - \frac{E_l(y)}{n_{inv}}\right] n_{bc} \qquad (8)$$

b. Depth of Discharge, DOD: This represents the percentage of battery capacity which is discharged expressed as a percentage of maximum capacity. It is termed as deep discharge when discharge reaches up to at least 80% DOD.

c. Terminal voltage, V_t: When a load is present, it is the voltage between the battery terminals. The SOC and discharge/charge current both affect this voltage.

d. Open Circuit Voltage, V_{oc}: This represents battery voltage without applied load. V_{oc} is influenced by the battery's SOC so it increases as SOC of battery increases.

V. *Inverter:*

Power inverters transform electrical energy from DC form to AC form. Its goal is to maintain an equilibrium in the flow of electricity through the DC and AC components. The standalone inverters are suited for use in remote locations since they are made to run on independent, utility-free power systems. Efficiency of an inverter for converting DC to AC is about 90% or greater [23]. A modified sine wave relates more in shape to that of a sine wave, but it is similar to a square wave. The modified sine wave inverters provide a cheap and easy solution for powering AC devices. The AC power supplied by a wall socket may be exactly matched by pure sine wave inverters [25]. When evaluating the type of inverter to be used certain factors like power quality, power rating and efficiency of inverter should be considered. Inverters should ideally have continuous ratings that are around 30% greater than the highest power needed to supply the load. The following equation can be used to determine how many inverters an off-grid hybrid system needs [24],

$$N_{inv} = \frac{P_L}{P_{inv}} \qquad (9)$$

Here, N_{inv} is the required number of inverters, maximum load power is denoted by P_L and inverter power is denoted by P_{inv}.

C. Sizing of System Components

It is initially necessary to determine the power needs of the user in order to size the components in the hybrid system. Once it is determined the following steps are followed for sizing all the components.

I. *Sizing of Solar PV Module:*

The system's efficiency determines how much power is needed [14].

$$Total\ power\ required\ from\ PV\ array = \frac{Load\ Requirement}{Efficiency\ of\ the\ System} \qquad (10)$$

The input power, P_i of the system is calculated using the incident solar radiation,

$$P_i = G_i\, x \times A_m \qquad (11)$$

Here, G_i is the incident solar irradiance W/m^2 and A_m is the effective area of cells in a module.

The output power, P_o of the PV module is given by,

$$P_o = V_{dc} \times I_{dc} \qquad (12)$$

Here, V_{dc} is the DC operating voltage and I_{dc} is the DC operating current.

Energy produced by one module in a day is,

$$E_{1Day} = \frac{Actual\ Power\ Ouput}{Daily\ operation\ hours} \qquad (13)$$

The number of modules required in PV array is given by,

$$n = \frac{Power\ output\ required\ from\ PV\ array}{Power\ rating\ of\ unit\ module} \qquad (14)$$

Efficiency of PV array is given as,

$$\eta_p = \frac{Total\ Power\ used\ from\ PV\ array}{PV\ array\ capactity}\ x\ 100 \qquad (15)$$

To capture the most solar energy possible, the collector should be faced north if in the southern hemisphere and the tilt angle is given as,

$$T = \beta_N - 90 = 7.72° \qquad (16)$$

II. *Sizing of Wind Turbine:*

The wind power density is expressed as,

$$P_d = \frac{1}{2}\rho_a v^3 \qquad (17)$$

where ρ_a and v^3 are the air density and velocity of wind respectively.

To find out the actual power density that will be converted to useful energy, the coefficient of performance C_p , transmission losses T_l and generator losses G_l of the wind turbine need to be considered into equation 17 as the overall loss factor L_f,

$$L_f = C_p \times T_l \times G_l \quad (18)$$

$$P_{d-act} = \frac{1}{2} L_f \rho_a v^3 \quad (19)$$

Annual energy density of the turbine is found as,

$$E_{d-act} = P_{d-act} \times no\ of\ hours\ per\ year \quad (20)$$

Rotor size is calculated as,

$$Swept\ Area = \frac{Total\ annual\ energy\ required}{Useful\ energy\ density} \quad (21)$$

Radius of rotor blade,

$$R = \sqrt{\frac{Swept\ Area}{\pi}} \quad (22)$$

Power rating of the turbine

$$P_r = P_{d-act} \times A_r \quad (23)$$

The turbine's actual rated power should be

$$P_{r-act} = P_r \times C_f \quad (24)$$

Speed of turbine,

$$N = \text{v} \times 60 \times TSR \ \frac{\text{v} \times 60 \times TSR}{2\pi r} \quad (25)$$

TSR represents tip speed ratio.

III. *Inverter Sizing:*

The required inverter power is calculated as,

$$P_{\text{inverter}} = \frac{P_P(\text{W})}{\eta_{\text{INV}}} \quad (26)$$

Inverter efficiency is ideally taken to be 90% [17].

IV. *Battery Sizing:*

Required storage value for the system is,

$$P_{\text{Ah}} = \frac{P_{\text{load}}(\text{ solar }) + P_{\text{load}}(\text{ wind })}{V_{\text{battery}}} \quad (27)$$

The no of batteries required is,

$$Amount\ of\ batteries\ needed = \frac{Storage\ value\ of\ system}{Battery\ capacity\ (Ah)} \quad (28)$$

D. Selection of System Components:

The following assumptions are taken into consideration for selection of components:

a. Inverter has an efficiency of roughly 90% when converting DC power to AC power.
b. 48 V is the battery voltage required for operation.
c. Sunlight available in a day is 7 hrs/day.
d. Operating factor of PV module is taken to be 0.8.
e. Coefficient of performance for wind turbine is taken as 0.4.
f. Capacity factor for wind turbine is 0.3.
g. Density of air is 1.168 kg/m^3.

I. *Wind Turbine and Solar PV Selection:*

Based on the proposed calculations mentioned in section 5.3 and using the above assumptions the required sizing of wind turbine and solar PV panel for the SWHES was carried out. The wind turbine selected is AWS HC 650; its power curve is depicted in Fig 15. The selected solar panel is Trina Duomax PEF14 which is a residential scale polycrystalline module with 72 cells. For the designed system only one solar module and wind turbine was needed to be used in combination with the wind turbine. The specifications of the wind turbine and solar panel are shown in Table III and IV.

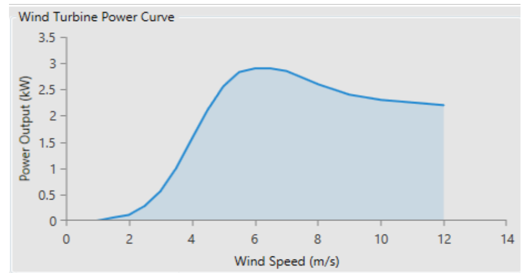


Fig. 14. Power curve for AWS HC 650.

TABLE III
Specifications of Wind Turbine

Rated Capacity	650.00 W
Rated Wind Turbine Voltage	12 V to 48 V
Cut-in Wind Speed	2.00 m/s
Blade Number	3.00
Rotor Diameter	2.20 m
Cut-out Wind Speed	8.5 m/s
Hub Height	12.00 m
Tip Speed Ratio	8.50

TABLE IV
Specifications of Solar Panel

Rated Capacity	320 W
Maximum Power Voltage	37.20 V
Maximum Power Current	8.60 A
Open Circuit Voltage	45.40 V
Short Circuit Current	9.23 A
Module Efficiency	16.30 %
Module Dimensions	1978 x 992 x 6 mm
Nominal Operating Temperature	44.0 °C

II. *Inverter and Battery Selection:*

The Inverter and Battery selected was Kirloskar KSG-I-1K and BAE Sundepot 48-350 respectively. The selection is compatible with the whole hybrid system and its specifications are listed in Table V and VI.

TABLE V
Specifications of Inverter

Maximum Input Power	1 kW
Input Voltage	48 V
Input Current	10 A
Power Factor	1
Efficiency	90 %

TABLE VI
Specifications of Battery

Nominal Capacity	320 Ah
Nominal Voltage	48 V
Minimum state of charge	20 %
Storage Capacity	6 kWh
Efficiency	90

VI. SYSTEM SIMULATIONS:

The operation of a system architecture plotted in HOMER determines if the designed system can meet the electric demand under the specified conditions [26]. Optimization, simulation and sensitivity analysis are the three functions carried out using HOMER. The specifications of the selected components are incorporated once all the key components are first introduced to the software interface. The solar and wind resource data like the average wind speed and solar irradiance data are fed into the software. The system architecture made in the software is shown in Fig 16.

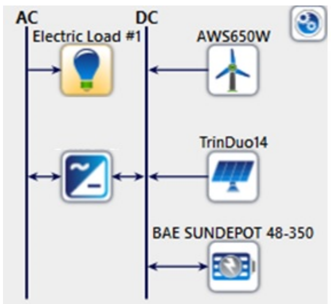


Fig. 16. System Architecture.

The overall power generation of components are shown in Table VII. It was discovered that each power source contributes a specific proportion of the overall power depending on the component specifications. The wind turbine generates a higher share with 2259 kWh/yr since the capacity of this component was on the higher side compared to solar PV module.

The average output in respect to the panel's rated capacity served as the foundation for the PV panel results. Average output was determined to be 80.31 W with a 20% capacity factor. Both temperature as well as solar irradiation in Vigakot was taken into consideration to obtain the optimum results of energy production from the solar panel. The solar panel was estimated to operate for 4,378 hrs/yr having a PV penetration of 92.8 %. The minimum and maximum output from the PV panel is 0 W and 405 W respectively. Solar PV panel's DMapp is shown in Fig. 17, and it is evident that the panel is able to provide adequate power for an entire year as long as there is sunlight.

TABLE VII
Energy Production contribution of each power source.

Production	kWh / yr	%
Trina Duomax PEG14	728	24.4
AWS HC 650	2259	75.6
Total	2987	100

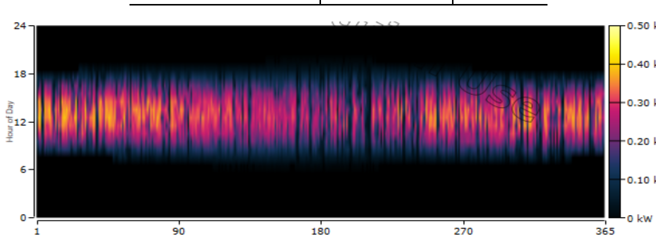


Fig. 17. PV output variation throughout the year.

The results for the wind turbine showed that the mean output after considering all the losses is 258 W with a capacity factor of 39.7 %. The total energy production from the wind turbine is found to be 2259 kWh/yr and it can operate up to 8,620 hrs/yr. The minimum and maximum power output from the turbine was 0 W and 658 W respectively. Fig. 18 displays the wind turbine output variation for a year and it is clear from the DMapp that the wind energy is unevenly distributed in a day but it still can be utilized successfully with the help of battery banks used in the system as energy storage device.

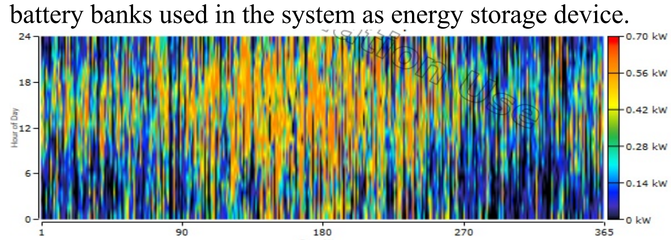


Fig. 18. Wind turbine output variation throughout the year

It is also to be noted from Fig. 19 that the battery can sustain a good state of charge (SOC) of 90% to 100% throughout the year. The battery's performance is significant since the hybrid system depends heavily on the battery's state of charge (SOC), which maintains a steady supply to the loads.

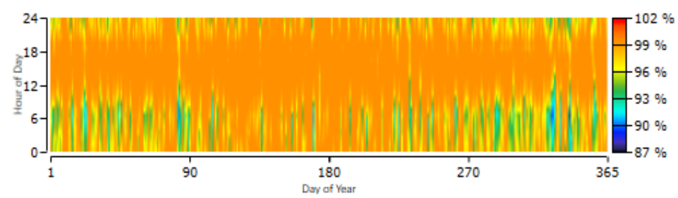


Fig. 19. Battery SOC throughout the year

The monthly simulation of the system demonstrates a good supply of electricity for a year. Hence this system can be used to power off grid rural households. From Fig. 20 it is seen that months of October and November has the lower simulated energy production, but this can be taken care of since the battery used in this design is of a higher storage capacity which is shown by the status of charge (SOC) plot.

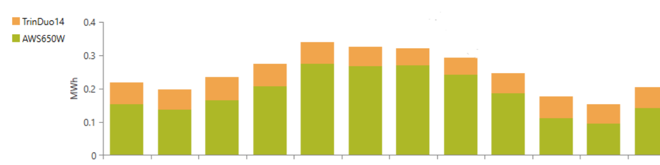


Fig. 20. Simulated monthly average energy production for the hybrid system.

The simulated hybrid system is projected to produce a total of 2,987 kWh/yr of energy which is about 8.1 kWh/day. After considering all the system losses each household would require around 2.5 kWh/day hence this designed system can be deployed at the location for usage. So, it can be concluded that the designed SWHES is reliable and can produce continuous and constant power supply to the loads without any fluctuations.

VII. CONCLUSIONS

In the present research, a detailed framework for developing a hybrid system starting from sizing of the components till virtually deploying it in a real-life environment is reported. A case study is presented to establish the feasibility of the designed hybrid system using the simulation software. The output variation from both the units and the total energy generation from them is predicted using HOMER.

- The wind turbine is observed to generate 2259 kWh/yr which constituted a higher share of 75.6% of the hybrid system. It is estimated to operate up to 8,620 hrs/yr.
- The mean output of the PV panel is found to be 80.31 W with a capacity factor of 20 %. The PV panel is estimated to operate for 4,378 hrs/yr having a PV penetration of 92.8 %. The maximum output from the PV panel is 405 W. The energy production from the PV panel is found to be 728 kWh/yr and constituted a lower share of 24.4% in the hybrid system.
- The output variation from the PV panel and Wind Turbine is viewed from the generated DMapp. PV panel can supply enough power throughout a year as long as there was sunlight whereas Wind Turbine output is unevenly distributed in a day but can be rectified using battery banks.
- The overall hybrid system combining both solar and wind energy production for is 2987 kWh/yr. Hence, it is concluded that the designed hybrid is able to meet the demand of the households.

It is established through the simulation that the system is capable of supplying electricity continuously and without any fluctuations. Analysis carried out in this research will serve as a standard for researchers and energy consultants in this field who are interested in building up SWHES for electrification.

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