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## Probabilistic Method for Estimating the Level of Reliability of Solar Photovoltaic Systems for Households in Ghana

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### *Authors' contributions*

*This work was carried out in collaboration among all authors. All of them were highly involved in the concept, modeling, formulation, implementation, analysis and the writing of the paper. All authors read and approved the final manuscript.*

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## Abstract

Renewable Energy Resources have been identified among the most promising sources of harnessing power for industrial and household consumption but their power generations highly fluctuate so building renewable power systems without critical reliability analysis might result in frequent blackouts in the power system. Therefore, in this paper, a robust, effective and efficient design approach is proposed to handle the reliability issues. The study involves a Mathematical modelling strategy of the PV system to estimate the total PV power produced and the Bottom-Up approach for predicting the household load demand. The reliability is defined in terms of Loss of Load Probability. The design methodology was validated with a University Household. The data used for the analysis consists of daily average global solar irradiance and load profiles. The results revealed that throughout the year, November-February is where the system seems to be more reliable. Also, the results indicated that without buck-up systems, the system would experience an average annual power loss of 17.8753% and thus, it is recommended that either solar batteries or the grid are used as backup system to achieve a complete level of reliability.

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## 1 Introduction

The demand for energy around the globe keeps growing exponentially and due to the expensive and scarcity nature of the non-renewable sources of energy like fossil fuels, keeping up this demand over time is extremely difficult [1]. Due to this, much attention is being shifted to more environmentally friendly, replenishing and cost-effective energy sources [2]. Renewable Energy Sources (RES) of energy such as the wind, solar, hydro, ocean tidal, etc., seem to be the most preferred options.

However, since their generations of power is purely stochastic in nature (completely depend on climatic conditions which are extremely complex to be predicted accurately), and instances such as the technical connection failures, the set-up Renewable Energy Supply System (RESS) might experience frequent load failures or blackouts [3]. In other words, they are unable to guarantee a reliable and continuous supply of energy at a cost that can compete with the conventional power from the grid since the reliability level is highly influenced by the system's technical operation and the intermittency in the RES.

Therefore detailed analysis on the sustainability and cost-effectiveness of the RESS might not be realistic without a critical assessment of the system's reliability [4]. Extensive reliability analysis and assessment could aid in setting up a more robust and optimal planning strategy for solar energy designers [5].

This has motivated many authors to conduct various researches on the reliability analysis of the RESS. For instance, Fara et al. [6] conducted a reliability analysis of PV systems for specific applications where the focus was to get a much more stable and sustainable operation of a PV system, in [7], a reliability analysis was carried out and it was concluded that to achieve a higher level of reliability, a small wind turbine with small power electronics must be used, again, Essan [8] built a methodology to assess the reliability for islanded hybrid PV-diesel-battery system in society at Nigeria, Sayed [9] also conducted a study which assessed and analyzed PV grid-linked reliability, its availability and the maintainability. Though the reliability problem has been addressed in various forms by different researchers it remains a complicated problem, that is, given energy demand, it is really difficult to estimate the reliability level of the RESS so that it could meet such demand due to the uncertainty and some technical failures in the RESS [10]. The set-up in Ghana, for instance, is mostly based on experience and intuition, which could sometimes result in either overproduction or underproduction of power [11]. Furthermore, most of the feasibility studies on PV systems did not consider critical analysis and assessment of the system's reliability [9]. The few studies that considered the reliability analysis were purely based on the manufacturers' data which according to [7], could yield results that have no proper or concrete justification. Also, though there have been a lot of studies on the design of solar systems in Ghana, none of these considered a critical analysis and assessment of the system reliability [4]

Therefore, in this paper, a robust, effective and efficient design approach is proposed to handle the reliability issues of RESS in Ghana. The study involves a Mathematical modelling strategy of the various components for measuring reliability.

To achieve the defined objective, we outline the paper in the following manner: section one summarizes the background of the study, the problem statement and the research objectives. In section two, the details of mathematical modelling of the PV system and the load forecasting

are presented. The implementation of this modelling strategy with data from Ghana through simulations in the MATLAB environment is carried out in section four. The results from the simulations are also analyzed and discussed in this section. And finally, conclusions and recommendations are outlined in the fifth section.

## 2 Materials and Methods

This section discusses the various mathematical methods to estimate the components for calculating the reliability of the RESS.

One of the effective ways to estimate the reliability of a RESS for a household or community is to accurately predict the total load demand and the total energy produced by the PV system [12] which have been discussed in the next section

### 2.1 Methods for modeling electricity demand for households

Mostly, the real household consumption data is not available for most homes in Ghana and some parts of the world because of unavailability of electricity usage monitors which measure precisely the amount of power a gadget consumes [13]. As a result, various authors have proposed different methods to predict the total household energy consumption [14],[15],[16],[13],[17],[11],[4],[18],[19],[20],[21],[22],[23],[24],[25],[12],[26],[27],[28],[29],[30],[31],[32],[33],[34],[35],[36],[37],[38],[39],[40],[41],[42].

For instance, in the following studies, [33],[34],[35],[36],[37],[38],[39],[40],[41] the Bottom-up method was applied to forecast households energy consumption and they concluded that the results obtained were highly promising. Also, in these studies [26],[27], [28],[29],[30],[31],[32], artificial neural networks was applied to forecast residential load in short-term. Forecasting approaches like the fuzzy logic were employed in the following studies [24],[25],[12],[42] to predict the household energy demand. Other robust methods like optimization and wavelet were also applied to forecast residential loads in the following studies [18],[19],[20],[21],[22],[23].

Though many approaches have successfully predicted the household load with high speed, in a situation where more priority is assigned to accuracy, the Bottom-up method dominates over others [32]. Again, the Bottom-up approach captures the effect of each household gadget in estimating the total energy demand [35]. Therefore, in this paper, it is used to forecast the household energy demand

#### 2.1.1 The bottom-up method

The main logic behind the Bottom-up approach is to deduce the overall energy consumption of the household using the appliance wattage. This approach is very robust as it could capture the effect of each household gadget in estimating the total energy demand [41]. In [41], the details of this method are presented. Its mechanism is depicted by Fig. 1.

#### 2.1.2 Factors affecting energy consumption

In this paper, the following simplifying assumptions are made in the generation of the load:

- the effect of external Variable such as Mean temperature is ignored.
- Consumer availability: Weekdays consumption does not differ from Weekends.

Depending on the trend of consumption, an appliance could be on at the time of the day and its consumption cycle will be factored into the total load curve of the household. The activation of an

appliance is checked using a probability function called Starting Probability function ( $P_s$ ) given as [41]:

$$P_s(I, t, h) = P_h(I, h)f(I, d)P_{step}(t)P_{sat}(I) \quad (2.1)$$

where  $I$ ,  $t$ ,  $h$  are the appliance, the time step (mins), and the hour of the day respectively,  $P_h(I, h)$ : hourly probability factor which models the levels of activity of each appliance within a day  $f(I, d)$ : the mean daily starting frequency, which models the average time each appliance is used,  $P_{step}(t)$ : the step size scaling factor scaling the probabilities based on  $t$ ,  $P_{sa}(I)$ : a probability indicating the availability a special class of appliances present in a particular household.

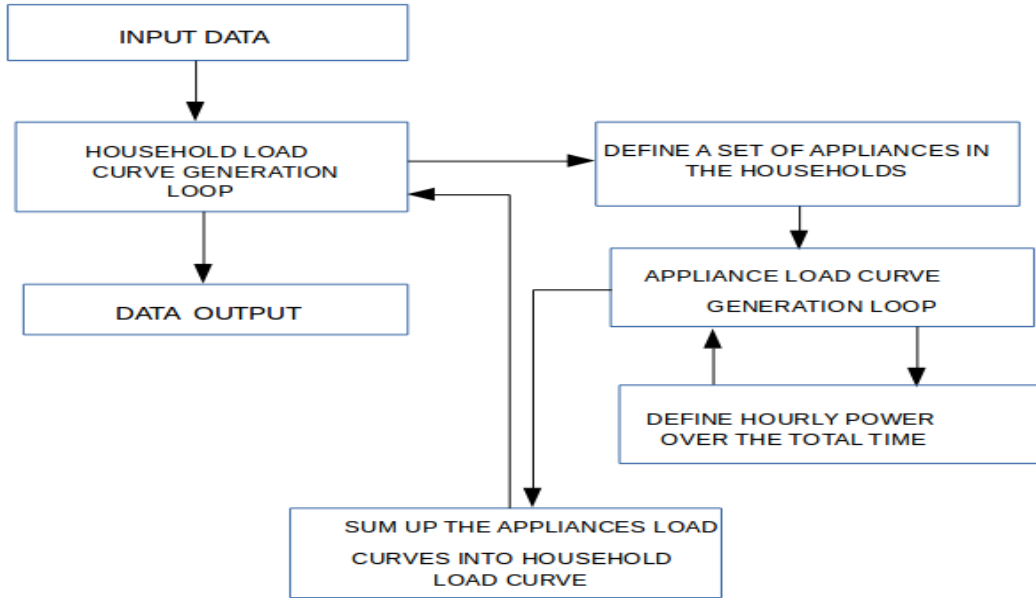


Fig. 1. Bottom-Up Method for Household Load Generation

The monthly average energy consumption by a household by active and standby consumption parameters can be generated by the equation [41]:

$$E_m = \frac{30 * \left( 3600 * W_{stan} + f(I, d) \sum_{n=1}^N W_n(I) * t_{cycle} \right)}{3600000} \quad (2.2)$$

where  $N$ ,  $W_{stan}$ ,  $W_n(I)$  are the total number of appliances, nominal and standby power respectively.

Another factor required for the reliability analysis is the model amount of PV power produced by the RESS, In this paper, we derive a mathematical model to estimate it in the next section.

## 2.2 Modeling of the photovoltaic (PV) system

To obtain the total power from the PV, it is desired to formulate a function that converts the energy from the sun into electricity. Modelling of the PV system helps in assessing the general PV system performance [10]. Solar energy can be generated by different methods: **Solar thermal energy, Photovoltaic cells, and concentrated solar power systems (uses mirrors or lenses)**. In this, we use the solar PV panel to generate the expected power for the household since it is one of the simplest and inventive approaches of exploiting energy from the sun [43]. The panel is made up

of many cells of semi-conductors that converts the sun's radiation to electricity. The sun's photon strikes these cells and electrons are then released forming electricity [43]. This phenomenon is depicted by Fig. 2.

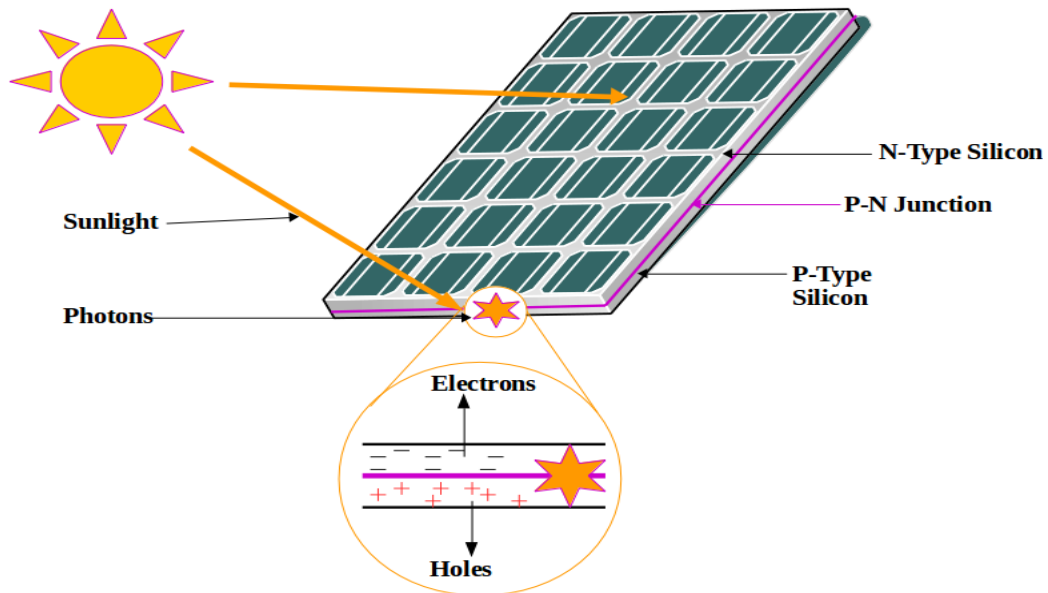


Fig. 2. PV system

### 2.2.1 The solar geometry

For any design in the solar system, it is always important to fathom the sun's movement relative to the horizontal plane and North-South direction. This is described by the following angles that are shown in Fig. 3:

where:

$\theta_z$	:Zenith angle
$\theta_I$	:Incidence angle
$\alpha$	:Altitude angle
$\gamma_s$	:Sun's Azimuth angle
$\gamma_{pv}$	:Panel's Azimuth angle
$\beta$	:Tilt angle

Other vital angles required to compute the angles between the solar panel and sun rays are the:

**Latitude** ( $\phi$ ): is the angle (measured as if from the centre of the Earth) between a point and the equator.

**Hour angle** ( $\omega$ ) : Angle representing the position of the sun w.r.t clock hour and with reference to the sun's position at noon.

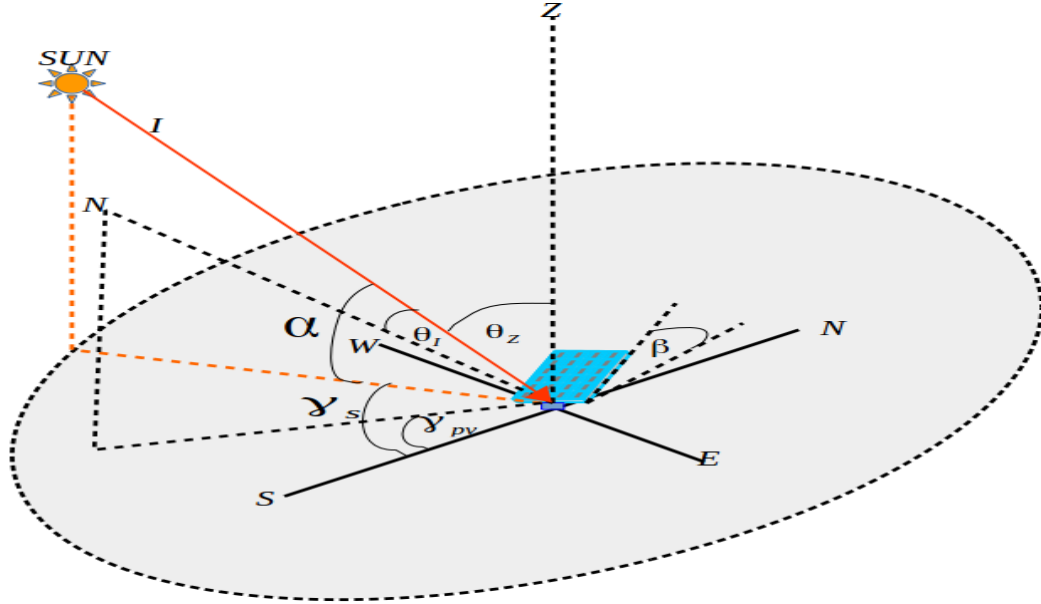


Fig. 3. The Geometry of the PV System

**Declination Angle, ( $\delta$ ):** It lies between the plane orthogonal to a line between the earth and the sun and the axis of the earth and it is estimated by the Equation [44]:

$$\text{declination angle}(\delta) = 23.45 \frac{\pi}{180} \sin \left[ 2\pi \left( \frac{284 + N}{36.25} \right) \right] \quad (2.3)$$

for  $N$  being the day's number.

**Altitude, ( $\alpha$ ),** is estimated by the following equation [45]:

$$\alpha = \sin^{-1} (\cos \delta \cos \omega \cos \phi + \sin \delta \sin \phi) \quad (2.4)$$

**Hour angle, ( $\omega$ ) :** This can also be computed by the following equation [45]:

$$\omega = \sin^{-1} \left( \frac{\sin \alpha - \sin \delta \sin \phi}{\cos \phi \cos \delta} \right) \quad (2.5)$$

**The Solar Azimuth Angle, ( $A_z$ ):**

$$A_z = \text{sign}(\omega) \left| \cos^{-1} \left( \frac{\cos \cos \theta_z \sin \phi - \sin \delta}{\sin \cos \theta_z \cos \phi} \right) \right| \quad (2.6)$$

**The sun's incidence Angle, ( $\theta_i$ ),** can be estimated by [44]:

$$\begin{aligned} \cos(\theta_i) = & \sin \phi \sin \delta \cos \beta + \cos \phi \sin \delta \cos A_s \sin \beta \\ & + \cos \omega \cos \phi \cos \beta \cos \delta - \cos \delta \sin \phi \sin \beta \cos A_s \cos \omega \\ & - \sin \beta \cos \delta \sin \omega \sin A_s \end{aligned} \quad (2.7)$$

From Equation (2.7), if the panel is on the horizontal surface,  $\beta = 0$ , and thus Equation (2.7) becomes:

$$\cos(\theta_i) = \cos \theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \quad (2.8)$$

When the the tilted panel faces the equator,  $A_s = 0$  and we have:

$$\cos(\theta_i) = \cos \omega \cos (\phi - \beta) \cos \delta + \sin (\phi - \beta) \sin \delta \quad (2.9)$$

### 2.2.2 Estimation of solar irradiance on tilted surfaces

The solar radiation intensity (power) falling on a surface (area) is called Solar irradiance and it is measured in  $W/m^2$  or  $kW/m^2$ . The total amount of solar radiation energy integrated over a period of time is the solar irradiation and it is measured in  $(J/m^2)$ . Three components of global irradiance: **Beam (direct) irradiance, Diffused irradiance, and the Reflected irradiance**. The solar irradiance is always measured on flat surfaces and these measurements are used to estimate the total irradiance falling on sloped surfaces [44].

The only types of irradiance that are absorbed by the horizontal surface are the beam ( $E_{Hb}$ ) and diffuse ( $E_{Hd}$ ) so the global irradiance on horizontal surface  $E_G$ , can be stated as [45]:

$$E_G = E_{Hb} + E_{Hd} \quad (2.10)$$

However, on the tilted surface, a portion of the reflected irradiance is absorbed and thus the global irradiance ( $E_T$ ) on a sloped surface can be estimated as [44]:

$$E_T = R_b E_{Hb} + F_d E_{Hd} + F_g \rho E_G \quad (2.11)$$

Where  $\rho$  is the ground reflectance (albedo)  $\in [0.2, 0.7]$ ,  $F_d$  represents the diffused tilt factor,  $R_b$  represents the tilt factor of the beam radiation,  $F_g$  denotes the ground reflected tilt factor.

**NB:** These factors are the ratio of measured horizontal irradiance to that of the irradiance on the tilted surface. Each of these factors is determined in the following sections.

### 2.2.3 The diffused and reflected components on a tilted panel

The diffused irradiance on the panel can be estimated by the Liu and Jordan PV Isotropic model [44]. Since the horizontal surface has no reflected irradiance measurements, the amount of irradiance reflected on the panel is found by the product of  $E_G$  and the factor  $F_g$  [45]. From the Fig. 4, the tilt reflectance and diffused factors can be obtained by trigonometric ratios as:

$$I_{d,t} = 2 \int_0^{\frac{\pi}{2}} I_{b,n} \cos \theta_i d\theta_i = 2I_{b,n} \quad (2.12)$$

$$I_d = \int_0^{\frac{\pi}{2}-\beta} I_{b,n} \cos \theta_i d\theta_i + \int_0^{\frac{\pi}{2}} I_{b,n} \cos \theta_i d\theta_i = I_{b,n}(\cos \beta + 1) \quad (2.13)$$

$$R_d = \frac{I_{d,t}}{I_d} = \frac{I_{b,n}(\cos \beta + 1)}{2I_{b,n}} = \frac{1 + \cos \beta}{2} \quad (2.14)$$

Similarly, we obtain  $R_g$  as:

$$R_g = \frac{1 - \cos \beta}{2} \quad (2.15)$$

### 2.2.4 Calculation of beam component

The direct component is estimated from the beam irradiance on the horizontal surface [44].

In Fig. 5, if  $I_{b,n}$  denotes the rate of horizontal irradiance and  $I_{b,t}$  that of a tilted panel, then it can be deduced that:

$$R_b = \frac{I_{b,t}}{I_b} = \frac{I_{b,n} \cos \theta_i}{I_{b,n} \cos \theta_z} = \frac{\cos \theta_i}{\cos \theta_z} \quad (2.16)$$

where  $\cos \theta_z$  and  $\cos \theta_i$  are defined by Equations (2.8) and (2.9).

Therefore from Equations (2.14), (2.15) and (2.16), Equation (2.11) becomes:

$$E_T = \begin{pmatrix} \cos \theta_i \\ \cos \theta_z \end{pmatrix} E_{Hb} + \left( \frac{\cos \beta + 1}{2} \right) E_{Hd} + \left( \frac{1 - \cos \beta}{2} \right) \rho_g E_{HG} \quad (2.17)$$

The power produced by the PV panel at time  $t$  is given by [45]:

$$E_{pv}(t) = (\eta_{pv} K_{pv}) E_T(t) \quad (2.18)$$

where  $\eta_{pv}$  and  $K_{pv}$  are the PV modules efficiency and nominal capacity respectively.

Thus, in this paper, Equation 2.18 is used to estimate the total energy from the PV system.

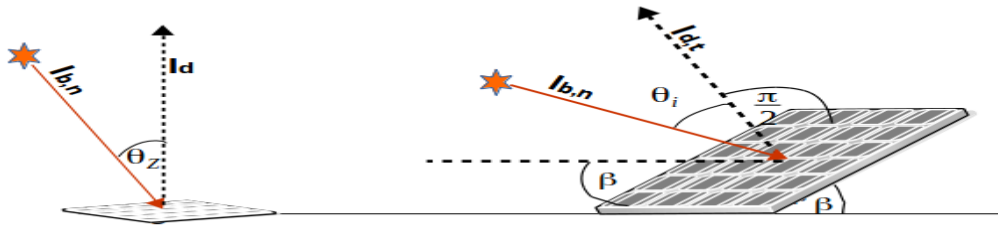


Fig. 4. Diffused Irradiance

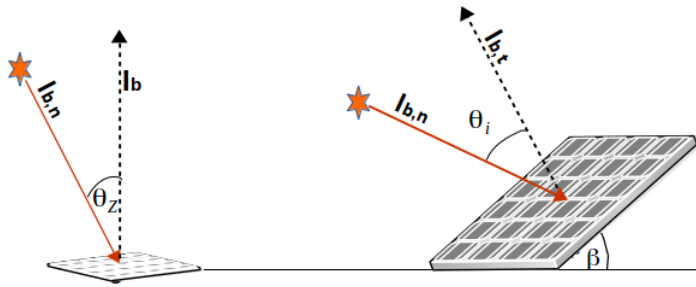


Fig. 5. Beam Component On Surfaces

### 2.3 Estimation of reliability of the PV system

The PV system reliability is the probability that the system is able to supply sufficient power to match the energy demand at all times. In this paper, it is estimated using the Loss of load probability (LLP). The LLP measures the average percentage loss of load demand in a power system [9]. It is indeed the total probability that the PV system would experience blackout and it is one of the main constraints that any power system must satisfy [8]. For each period during one year, the LLP is stated as:

$$LLP = \sum_{t=1}^{8760} \left[ \frac{E_m(t) - E_{pv}(t)}{E_m(t)} \right] \times 100 \quad (2.19)$$

Where  $E_m(t)$  and  $E_{pv}(t)$  are the hourly total load demand and PV power respectively.



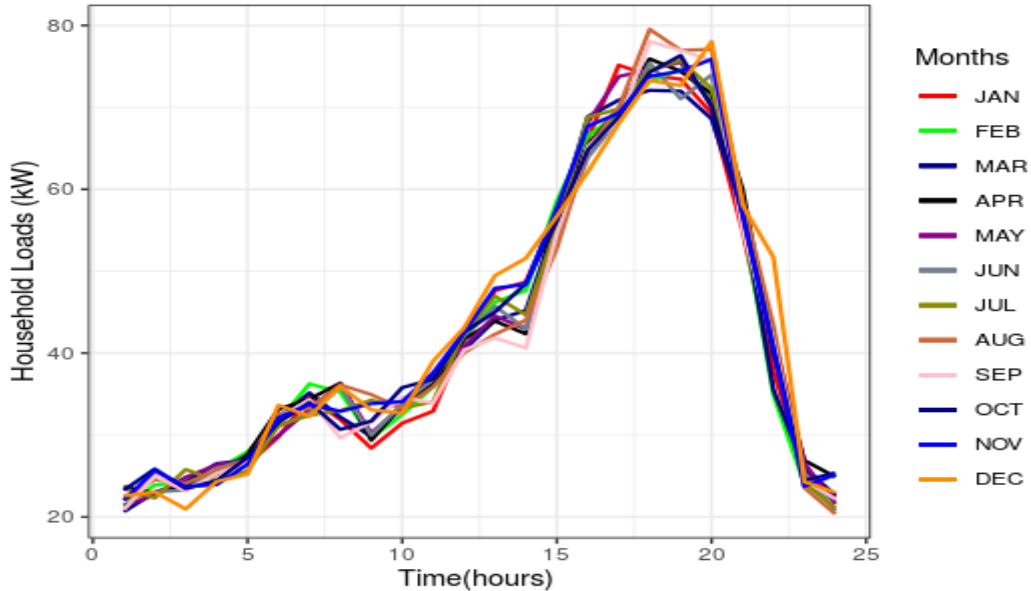
## 2.4 Case study

To test the design methodology, a 5kW RESS established for a household of five (5) rooms flat in KNUST, Ghana was considered. The main data used were the hourly load profiles estimated by the Bottom-up method and the measured hourly irradiance for each month within the year. The load demand data is shown in Fig. 6 below. The sample of parameters on households appliances can be found in Table 1.

**Table 1. Households Appliance Data**

Gadget (I)	$P_{sat}$	$W_n$ (W)	$W_{stan}$	$f$ mins	$t_{cycle}$
Microwave	0.93	1500	0	7.5	5
Fridge 1	1.0	110	8.10	40.5	12
Fridge 2	0.31	110	8.10	40.5	12
Coffee Maker	0.37	1000	0	1.12	6
Clothes washer	1.0	1200	0	0.75	54
TV 1	1.0	105	4	1.95	90
TV2	0.21	83	4	0.28	60
Air conditioner	0.93	1300	0	2.36	120
Lighting	1.0	120	0	18	30

The Fig. 6 is the average Households energy consumption data for all the months within the year. It is observed that between 5:00 AM and 8:00 AM, there is a little pressure on the power which describes the morning activities and between 3:30 PM to 8:00 PM, there is massive pressure on the power which depicts the numerous household activities that go on after days work.



**Fig. 6. Average Household Load Profiles**

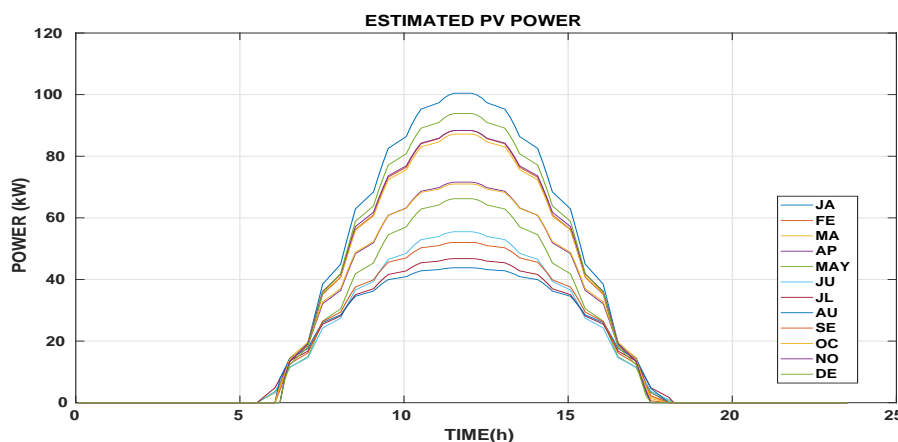
Another input data used to test the proposed methodology is one-year hourly solar irradiance. This data is estimated from measured solar irradiance on the horizontal surface obtained from KNUST.

The solar irradiance data has only the diffused and beam measurements so the reflected irradiance is estimated by multiplying the albedo 0.2 by the global irradiance on the horizontal surface. The estimation of the irradiance on the panel was done using the PV power function given by Equation (2.18) and the following parameters in the Table 2. The hourly time step is used because it is assumed that within a period of one hour, the effect of the variations in the RES is insignificant

**Table 2. Parameters of the PV panel**

Location	KNUST
Project lifetime (yrs)	25
Efficiency ( $\eta$ )	15%
Longitude	1.5654° W
Latitude ( $\phi$ )	6.6732° N
Reflectance ( $\rho$ )	0.2
Tilt angle ( $\beta$ )	30°
Azimuth angle ( $\gamma$ )	0°

The estimated solar power for the household is illustrated in Fig. 7.



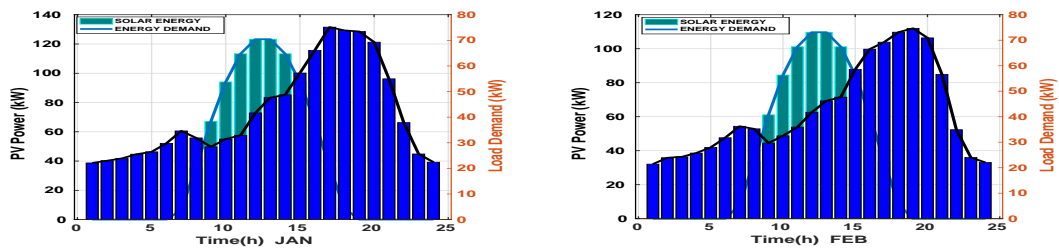
**Fig. 7. Hourly Estimated PV Power for the Household**

To measure the power deficiencies for each of the months within the year, the distributions of the power produced from the PV against the load demand of the household for all the months in the year are compared. This analysis and assessment would guide the designer to decide when and where to establish a RESS within the year and the country since it gives many ideas about blackout hours. It is observed from Figs. 8-13 that from 6 pm-6 am each day in all the months, the PV system does not produce significant amount of power and hence the system experiences a high level of power shortage. However, during the day, especially around 9 am to 4 pm, the average amount of power produced by the RESS exceeds that the load demand of the household and thus, a higher level of reliability is obtained.

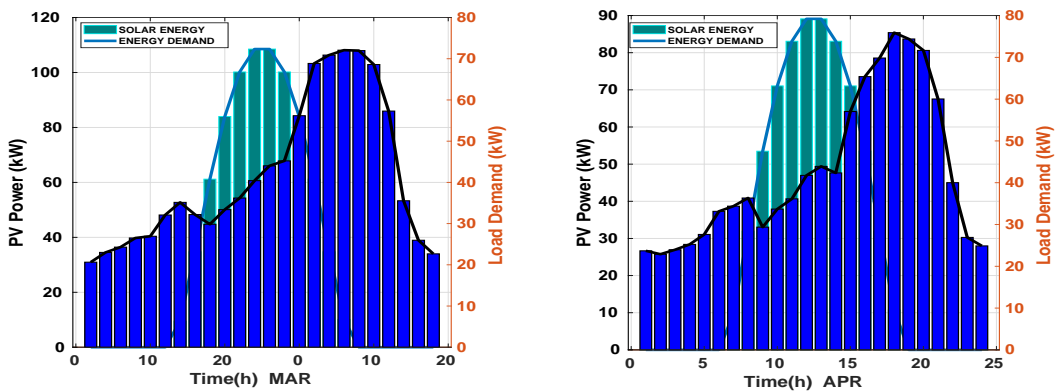
On monthly basis, the LLP in each month has been provided in Table 3 below. The results indicate that months such as January, February, November and December have the highest level of reliability and this could be the fact the sky is mostly clear during these months

**Table 3. Level of reliability of each Month**

Month	LLP(%)
January	17.2016
February	17.6704
March	17.9144
April	17.7623
May	18.3697
June	18.6793
July	17.7871
August	18.3931
September	18.1756
October	17.7445
November	17.5598
December	17.2461



**Fig. 8. Comparison of Load Demand and PV Power Produced from January-February**



**Fig. 9. Comparison of Load Demand and PV Power Produced from March-April**

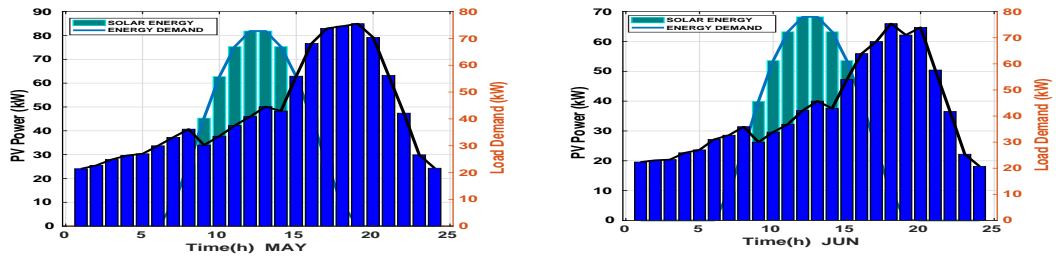


Fig. 10. Comparison of Load Demand and PV Power Produced from May-June

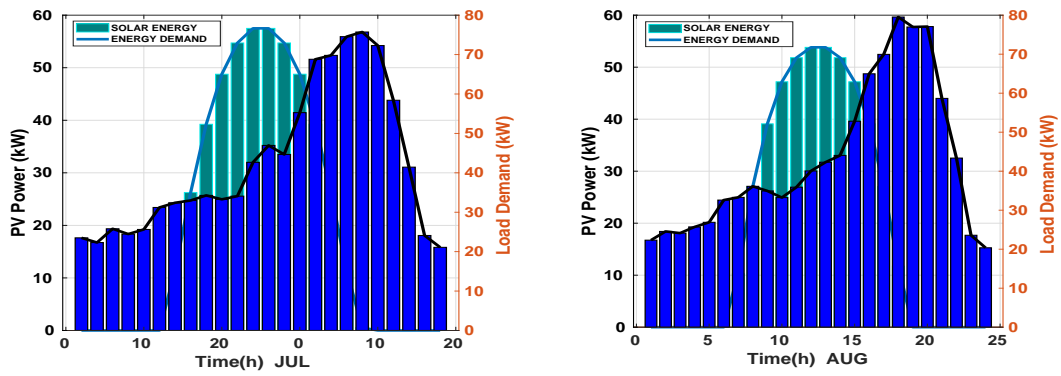


Fig. 11. Comparison of Load Demand and PV Power Produced from July-August

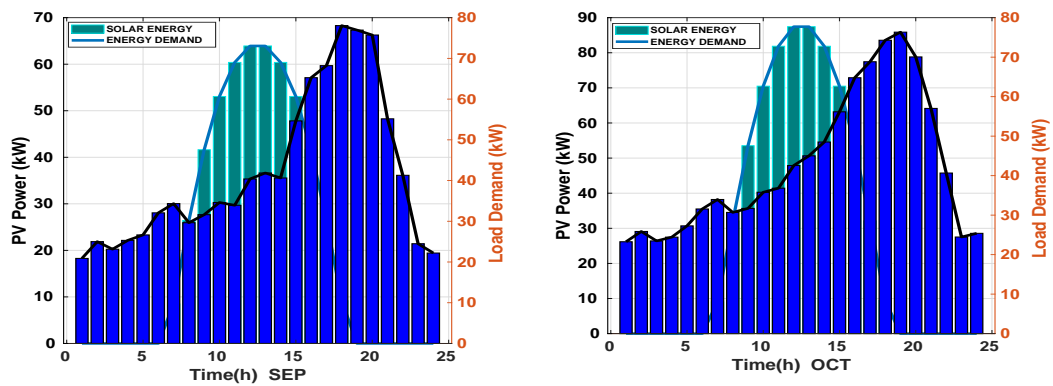


Fig. 12. Comparison of Load Demand and PV Power Produced from July-August

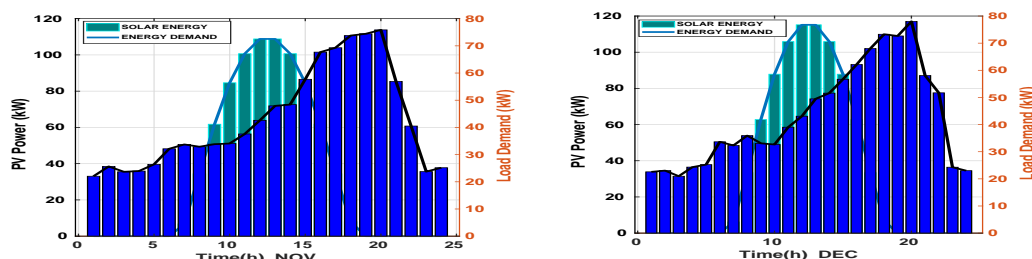


Fig. 13. Comparison of Load Demand and PV Power Produced from July-August

### 3 Conclusion

In this paper, a practical methodology has been developed to assess and analyse the level of reliability of Renewable Energy Supply Systems for Households. The approach involved an Isotropic PV model for estimating the global solar irradiance on tilted panels, the bottom-up method for household load forecasting and the Loss of Load Probability function for quantifying the reliability level. The results indicated that without buck-up systems, the RESS would experience an average annual power loss of 17.8753% and thus, it is recommended that either solar batteries or the grid be used as a backup system to achieve a 100% level of reliability.

### Data Availability Statement

All data used can be obtained upon request.

### Competing Interests

The authors declare that they have no competing interests and there was no funding for this study.

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