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Optimal Sizing Procedure for Standalone PV System for University Located Near Western Ghats in India

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Abstract— This paper presents an optimal sizing procedure and tracking for standalone photovoltaic system located in one of the remote areas of India. This work is based on the meteorological data in Thondamuthur region where Karunya University is located and load demand profile of Computer Technology Centre of Karunya University. The PV array tilt angle is designed optimally based on the optimization algorithm. The PV array can be tilted at various angles in order to receive maximum global solar energy in different season. This strategy of tilt angle adjustment can reduce the use of electromechanical or pure mechanical devices, reduce the number of site visits and increase the solar radiation capturing efficiency. PV array size and storage battery capacity are calculated based on numerical method and compared with intuitive method using MATLAB. It is proved in this paper that the system designed by intuitive method is more expensive than the system designed by the numerical method as the former is based on the worst month data.

Index Terms— Array size, Battery capacity, Optimal Sizing, Optimization of energy sources, PV tilt angle

I. INTRODUCTION

PV systems are clean, environment friendly and secured energy sources. However, the drawback of PV systems is the high capital cost compared with conventional energy sources. Nowadays many techniques are introduced to do optimization of PV systems so that the number of PV modules, capacity of storage battery, capacity of inverter and PV array tilt angle can be optimally selected. PV system size and performance strongly depend on solar energy and ambient temperature.

Coimbatore has latitude of 10.9397487° and longitude of 76.7458484°. The climatic condition of this region shows huge variation. Because of this fact the solar radiation is varying. This place has a very good potential for solar energy harnessing because of the long daily duration of sun shine hours and high levels of solar radiation. In other words the use of PV system might be feasible and therefore, deep technical evaluation, feasibility and size optimization studies must be done for this zone. The result of this study shows that the proposed systems can displace diesel generation significantly and the economical benefits of the resulting systems depended on load and renewable energy resources.

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Based on the main objective of this paper is the recommendation for optimal sizing of a standalone PV system for Karunya University. These recommendations include PV module/array optimum tilt angle, optimum PV array size and optimum capacity of the storage battery.

Finally a comparison between some methods for designing standalone PV system and the proposed numerical method is done in order to show the significance of the proposed method. In this paper, the meteorological data of Thondamuthur region is used along with load demand of Computer Technology Centre, Karunya University. In this work, best strategy for PV tilt angle adjustment is also done.

II. OPTIMIZATION OF PV ARRAY TILT ANGLE

The solar array is the only energy source in the solar photovoltaic system. The daily output of a solar array depends on solar irradiation falling on the PV panel. Since solar arrays are rated at a solar radiation level of 1000 W/ m^2 and a solar cell temperature of 25 °C, the peak sun hours (PSHs) are often used to represent solar irradiation so that the daily output of the solar array is easily calculated by using the peak watt (Wp) of solar array times the PSHs, where the PSHs is equivalent to the length of time in hours at a solar radiation level of 1000 W/m^2.

The orientation and tilt of a solar panel affect the amount of the collected solar energy yield. Therefore, solar panels must be tilted and oriented at optimum angles to collect the maximum solar energy available in a specific region. The preferred method to optimize the tilt angle of a solar panel is by applying mechanical devices that keep changing the tilt and the orientation of a solar panel periodically during the day [2]. But the capital cost of such a system is high and it consumes energy during tracking. Thus, changing the tilt angle and the orientation for a PV panel is found to be more feasible than applying an active sun tracker.

The components of incident global solar radiation on a tilt surface consider the global, direct (beam), diffuse and reflected solar energy on a tilt surface. The daily total radiation incident on a tilted surface G_{Td} is composed of direct B_{Td}, ground reflected R_{Td} and sky-diffuse D_{Td} components [4]:

$$G_{Td} = B_{Td} + D_{Td} + R_{Td} \qquad (1)$$

where, B_{Td} Daily direct solar radiation on a tilted surface ($kwhm^{-2}$);D_{Td} Daily diffuse solar radiation on a tilted surface ($kwhm^{-2}$);R_{Td} Daily reflected solar radiation on a tilted surface ($kwhm^{-2}$); G_{Td} Daily total solar radiation on a tilted surface ($kwhm^{-2}$);

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$$B_{Td}=R_b B_d \quad (2)$$
$$D_{Td}=R_d D_d \quad (3)$$
$$R_{Td}=R_r G_d \quad (4)$$

where, B_d Daily direct solar radiation on a horizontal surface ($kwhm^{-2}$); D_d Daily diffuse solar radiation on a horizontal surface ($kwhm^{-2}$); G_d Daily total solar radiation on a horizontal surface ($kwhm^{-2}$); R_b Ratio of the daily direct solar radiation incident on a tilted surface to that on a horizontal surface; R_d Ratio of the daily diffuse solar radiation incident on a tilted surface to that on a horizontal surface; R_r Ratio of the daily reflected solar radiation incident on a tilted surface to total solar radiation on a horizontal surface. B_{Td}, D_{Td} and R_{Td} depend on direct, diffuse and total radiation on horizontal surface. R_b, R_d and R_r are the ratio of the daily radiation incident on a tilted surface to that of a horizontal surface for direct, diffuse and reflected radiation, respectively and B_d, D_d and G_d are daily direct, diffuse and total solar radiation on a horizontal surface.
Substituting (2), (3), (4) in (1), we get

$$G_T = R_b B_d + R_d D_d + R_r G_d \quad (5)$$

Liu and Jordan have suggested that R_b can be estimated by assuming that it has the value which would be obtained if there were no atmosphere [6]. For surfaces in the northern hemisphere, sloped towards the equator, the equation for Rb is given as:

$$R_b = \frac{\cos(\Phi-\beta).\cos\delta.\sin\omega ss + \omega ss.\sin(\Phi-\beta).\sin\delta}{\cos\Phi.\cos\delta.\sin\omega ss + \omega ss.\sin\Phi.\sin\delta} \quad (6)$$

where, ωss is the sunshine hour angle, Φ is latitude of the specified region, β is the tilt angle, δ is the declination angle. The declination angle can be calculated using the equation :

$$\delta=(23.45°)\sin[360°(284+n)/365] \quad (7)$$

where, n is the day number in the year, with January 1 as 1.For northern hemisphere, the sunshine hour angle ωss is given by

$$\omega ss = \min\{\cos^{-1}(-\tan\Phi\tan\delta), \cos^{-1}(-\tan(\Phi-\beta)\tan\delta)\} \quad (8)$$

According to Badescu model, the formula for Rd is as follows [7]:

$$R_d = \{3 + \cos(2\beta)\} / 4 \quad (9)$$

Rr is calculated by using the equation

$$R_r = (1-\cos\beta) / 2 \quad (10)$$

Global solar energy on a tilt surface is finally derived to be

$$G_{TLT} = (G_d-D_d)\frac{\cos(\Phi-\beta).\cos DEC.\sin\omega ss + \omega ss.\sin(\Phi-\beta).\sin\delta}{\cos\Phi.\cos\delta.\sin\omega ss + \omega ss.\sin\Phi.\sin\delta} + D_d\frac{3+\cos(2\beta)}{4} + G_d\rho\frac{1-\cos\beta}{2}$$
$$= (G-D)*R_b + D*R_d + G\rho*R_r \quad (11)$$

where, ρ is the reflectance = 0.2 for sand land

In this research, meteorological data is taken for Thondamuthur region, where Karunya University is located. The data contain global solar radiation, diffuse solar radiation of each day. The data showing the radiation is given in table I. Fig. 1 shows the graph depicting the solar irradiation of the specified location.

TABLE I: MONTHLY MEAN SOLAR IRRADIATION DATA OF THONDAMUTHUR REGION

Month	Solar radiation (kW-hr/m^2)
January	5.8196145
February	6.7439883
March	6.9057964
April	6.6498324
May	6.6118635
June	5.3301152
July	4.8619028
August	4.7681799
September	2.8070207
October	2.2937474
November	4.2896862
December	4.9817255

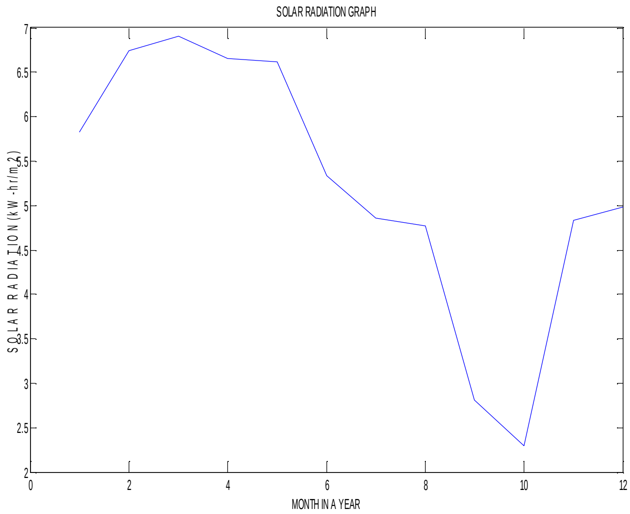

Fig. 1: Simulated monthly solar radiation graph

Algorithm for PV array tilt angle optimization

i. Define the specified location by its geographical coordinates (latitude and longitude).
ii. Obtain the global and diffuse solar radiations for this location.
iii. Calculate the direct solar radiation using (global solar radiation–diffuse solar radiation).
iv. Initialize the ground reflectance ρ (0.2 for sand land).
v. Set the tilt angle as Start=0 ; Step=1; Stop= 90
vi. Set the time span as Start=1; Step=1; Stop=365
vii. Calculate declination angle and sunshine hour angle ωss for each day.
viii. Calculate R_b, R_d, R_r for each tilt angle of that day.

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ix. Determine the global solar energy at each tilt angle.

x. Store the value of G_{tlt} in an array.

xi. Check if the maximum value of time span is reached. If no , proceed to the next time span else, go to step (xii)

xi. Calculate the average of G_{tlt} and store in an array.

xii. Check if the maximum value of tilt angle is reached. If no, proceed with next tilt angle value, else, go to step (xiv).

xiii. After reaching the maximum range, the stored solar energy values is searched for its maximum value in order to determine the optimum tilt angle which gives the maximum global solar energy.

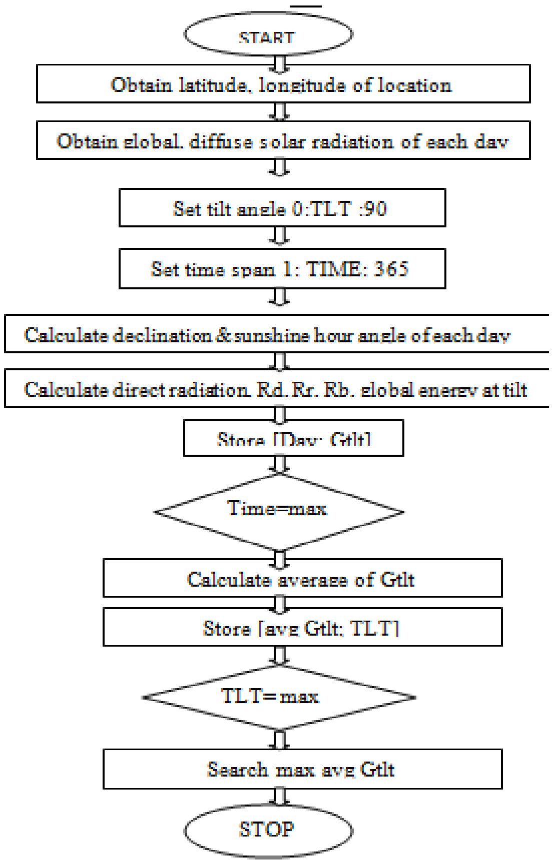

Fig. 2 : Optimization flowchart for PV array tilt angle

III.OPTIMAL SIZING OF PV SYSTEM ENERGY SOURCES

The sizing of stand-alone photovoltaic (PV) system is an important part of the system. Sizing of PV panel is the selection of accurate size of components in a system so that cost can be reduced and efficiency can be increased. If the system is larger in size than required, it can cause increase in cost. If it is smaller in size, shortage of demand is the result. Sizing decides the number of panels, type of panel required to capture solar energy, the capacity of battery that will store energy for the days of little sun and to determine the required characteristics of the rest of the elements that integrate the system. Optimal sizing is a must because the size of elements of installation must be balanced.

In this research, the monthly average load demand of Computer Technology Centre of Karunya University as in Table 2 is used in calculating the optimum size of the desired PV system. There are two main methods to design a PV system for the considered load demand. These methods are intuitive method and numerical method [3]. The intuitive method is based on the lowest monthly average of solar energy (worst month method) or the average annual or monthly solar energy without taking into account the random nature of solar radiation.

TABLE 2 : MONTHLY AVERAGE LOAD DEMAND DATA

Month	Load Demand (kW-hr)
January	701.411
February	705.786
March	712.651
April	705.411
May	702.891
June	705.411
July	701.291
August	703.366
September	691.970
October	686.711
November	697.411
December	700.291

The monthly average load demand of the building is simulated with the available data as in Fig. 3:

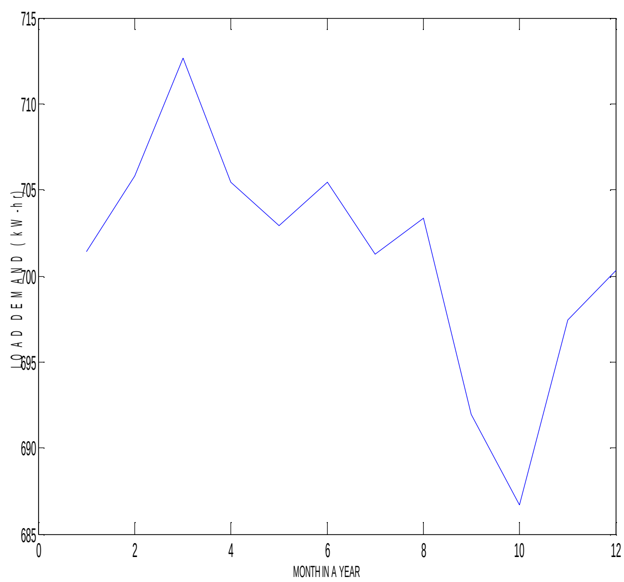

Fig.3 : Simulated load demand

A. Numerical Method

In numerical method, for each time period considered the energy balance of the system and the battery load state is calculated. These methods make the system more dependable and efficient. System reliability is defined as the load percentage satisfied by the photovoltaic system for long

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periods of time. The output or energy produced by a PV module/array is given by E_{pv}[1],

E_{pv}=Apv*Esun*□s (12)

where, E_{sun} is the solar radiation, A_{pv} is the area of PV module or array.

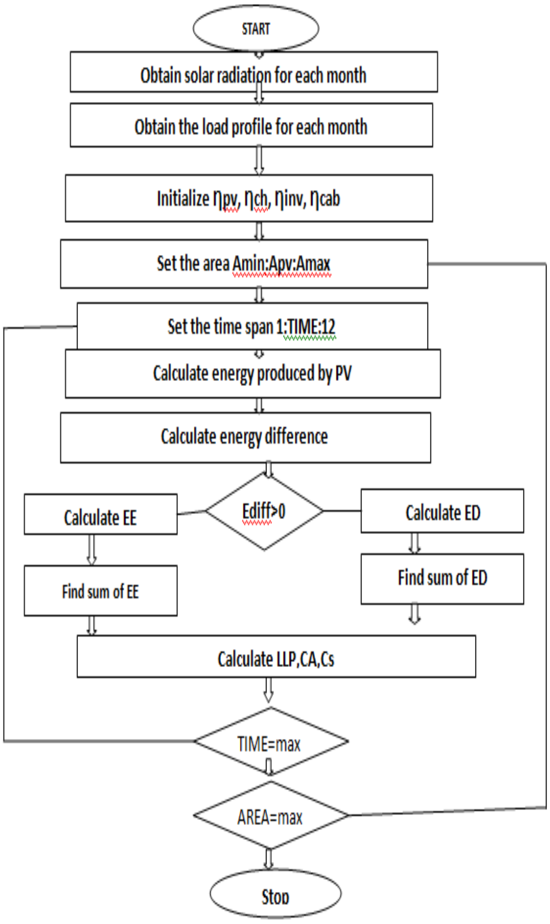

Fig 4 : Numerical method

The energy at the front end of a PV system or at the load side is given by,

Ediff=E_{pv}-Load demand (13)

The result is that it may be either positive (E_{PV} > EL) or negative (E_{PV} < EL). If energy difference is positive then there is an excess in energy (EE), while if it is negative then there will be an energy deficit (ED). The excess energy is stored in batteries in order to be used in case of energy deficit. Meanwhile, energy deficit is the disability of the PV array to provide power to the load at a specific time. The annual energy amount in the storage battery is given by,

Eb= (sum of energy excess- sum of energy deficit)*□ch (14)

where , □ch is the charging efficiency of a storage battery. The expected daily storage battery capacity, Cb can be calculated as follows,

Cb=Eb/366 (15)

In designing PV systems, it is important to know the energy availability. 100% availability of a energy means that the PV system is able to cover load demand in a year without any interruptions. The availability of a PV system is expressed using loss of load probability (LLP). LLP is the ratio of annual energy deficits to annual load demand and it is given by,

LLP= (Energy deficit) / (Load demand) (16)

PV array sizing and storage battery sizing are given respectively by,

CA=Epv/Load demand (17)

Cs=Cb/Load demand (18)

The numerical algorithm for sizing a PV system starts with defining some constants and initials such as load demand, PV efficiency, inverter efficiency, wire efficiency and charging efficiency. However, after defining the load demand (Wh/day), a range of PV array area must be set which gives different values of energy output. Subsequently, the energy difference is calculated. During the calculation of energy difference, arrays of EE and ED values will be constructed. At specific PV array area, LLP, storage battery size and PV array size are calculated and stored in arrays. This loop will be repeated till the maximum value of area is reached. Finally, plots of LLP vs. PV array size and storage battery size vs. PV array size are constructed.

B. Algorithm for Numerical Method

i. Obtain the solar radiation and load demand profile of each month.
ii. Initialize all the input parameters.
iii. Set the area of PV module as
Start= 338 ; Step=1; Stop=375
iv. Set the time span (month) as
Start=1; Step=1; Stop=12
v. Calculate the energy produced by PV panel
Epv=Apv*Esun*□s
vi. Calculate the energy difference
Ediff=Epv-Load demand
vii. If Ediff>0, determine the excess energy and its sum. If Ediff<0, determine deficit of energy and its sum.
viii. Calculate various output parameters such as LLP, PV array size, battery size.
ix. Check if the maximum time is reached. If no, proceed to the next time, else go to step (x).
x. Check if the maximum area is reached. Continue the loop until maximum area is reached.
xi. Plot the graph showing the relation between LLP and PV array size.
xii. Plot the graph between the PV array size and storage battery size.

C. Intuitive Method

The intuitive method is defined by as a simplified calculation of the size of the system carried out without establishing any relationship between the different subsystems or taking into account the random nature of solar radiation. These methods can be based on the month which gives the worst solar radiation. The major demerit of the technique is that difference in sizing of the PV panel can reduce the reliability on the system.

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The total amount of solar radiation energy expressed in hours of full sunlight per m² is called Peak Sun Hours. The peak solar radiation is defined as the equivalent number of hours per day, with solar irradiance equaling 1,000 W/m²,that would give the same amount of energy. PSH is taken based on the solar radiation of the worst month in hours per day. The total power is calculated by using the formula

Ppeak= (load*sf)/(PSH*□s) (17)

where, sf is safety factor which compensates the resistive losses and PV cell temperature losses, □s is the system efficiency.

The number of PV modules is obtained from the equation

N=Ppeak/Pm (18)

where, Pm is the power of PV module.

The total area of PV module is given by

A=N*Am (19)

where, Am is the area of PV module.

The battery capacity is calculated by using the formula

Cb= (Load*Adays)/(DOD*Vb*□b) (20)

Where, Adays is the autonomous days which is defined as the number of days a battery bank can provide the appliances to the system without getting recharged, DOD is the depth of discharge, Vb is the battery voltage, □b is the efficiency of battery.

D. Algorithm for intuitive method

i. Obtain the load demand and PSH for the worst month.
ii. Initialize all the input parameters of PV panel and battery.
iii. Calculate the total power Ppeak= (load*sf) / (□s*PSH)
iv. Determine the number of PV modules N= Ppeak / Pm
v. Calculate the area of modules A= N*Am
vi. Determine the capacity of storage battery Cb=(Load*Adays) / (DOD*Vb*□b)

IV. SIMULATION RESULT AND ANALYSIS

A. Result For PV Array Tilt Angle

In this research, the optimum angle of PV module/array is adjusted four times in a year. The solar radiation received in Coimbatore shows much variation due to rapidly changing climatic conditions. The adjustment of tilt angle is based on the solar radiation falling in a particular place.

TABLE 3: RESULTS FOR PV ANGLE OPTIMIZATION

MONTH	TILT ANGLE	GLOBAL SOLAR RADIATION ($kW\text{-}hr/m^2$)
Jan- March	30	6374.8
April-June	30	6626.9
July-Sep	20	5106.5
Oct-Dec	20	4517.8

The energy gain value obtained by tilting the PV panel is more than that when the PV panel is kept horizontal. It is clear that the best strategy of tilt angle adjustment is the four times adjustment in a year. This strategy proved to be the best in places where the climate shows significant variations throughout the year. The worst strategy of tilt angle adjustment is the annual (fixed) tilt angle. This adjustment can also reduce the number of site visits. It adds an advantage to the standalone PV system in remote areas. Most of the standalone PV systems are located at remote places that has some transportation difficulties. So, such type of tilt angle adjustment can reduce the number of site visits. Usually, the present day standalone PV system requires 12 site visits which cause much transportation difficulties and more transportation cost.

Result for PV system energy sources

Numerical method

The load profile is used to design an appropriate PV system using two methods; the intuitive method and the proposed numerical method. The system reliability as well as the cost of the energy produced by the system are used to evaluate the two design systems. In this research it is assumed to use a 10 Wp monocrytalline PV module. The area of this PV module is 415x268 mm. Finally, it is assumed that the number of the autonomous days is 3. The proposed numerical method which is executed by MATLAB is done based on real monthly average meteorological data and load demand.

From the PV array sizing curve in fig. 5, it is clear that the optimum point of PV array size at 0.01 LLP is 2.221. When battery sizing graph is plotted, the storage battery size corresponding to 2.221 PV array size is 0.03315.

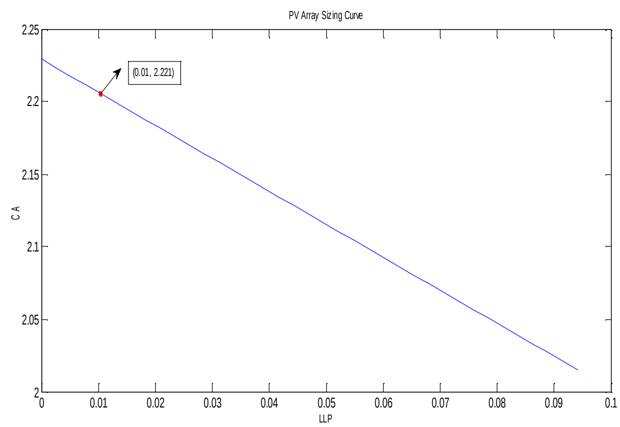

Fig. 5 : PV Array Sizing Curve

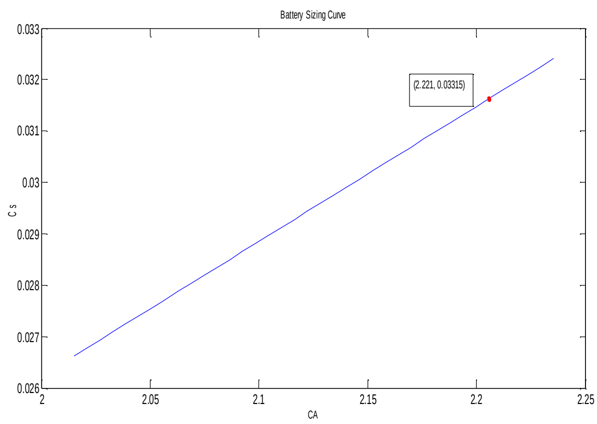

Fig. 6: Storage Battery Sizing Curve

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The table below shows some of the areas of PV module in m^2 along with LLP, PV array size and storage battery size.

TABLE 7 : RESULT OF NUMERICAL METHOD

AREA(m2)	LLP	CA	Cs	CB
375	0	2.2355	0.0324	22.6878
370	0.0103	2.2057	0.0316	22.1404
360	0.0365	2.1461	0.0301	21.0457
350	0.0627	2.0864	0.0285	19.9510
340	0.0889	2.0268	0.0269	18.8563

Intuitive method

The intuitive method considers the load demand and peak solar hours of the worst month of the year. Here, the worst month is taken to be October. In this method, total power, number of PV modules, total area of PV modules and storage battery capacity are calculated using MATLAB. Here, we have used a 10 Wp PV module with module area of 415x268 mm.

TABLE 8 : RESULTS OF WORST MONTH

PARAMETERS	VALUES
Load demand	686.171 kWh/day
Peak solar hours	2.2937474 h/day
Power of PV	1286.6 kW
Total power	560.90 kW
Number of PV modules	56090
Total area of PV modules	6238.4 m^2
Storage battery capacity	357.3807 Ah

The standalone PV system installed using the intuitive method is based on the details of the worst month. The installation area and storage battery capacity is as per the result obtained for the month of October.

TABLE 9: DISADVANTAGE OF INTUITIVE METHOD

MONTH	EXCESS LOAD (kWh)/year
JAN	1054
FEB	1331.27
MAR	1378.38
APR	1301.85
MAY	1290.49
JUNE	907.32
JULY	767.34
AUG	739.32
SEP	135.02
OCT	0
NOV	596.27
DEC	803.16

Due to this aspect, there is excess of power getting wasted. The table below shows the excess of load demand per month. From the table 9, it is clear that only in the month of October the complete demand is met with the installed PV system.

Cost Estimation

Intuitive Method

Based on the load demand and peak solar hours of the specified location, the power of PV module and storage battery capacity is determined. The unit cost of each component is obtained. With reference to these data, price of each component in a PV system is figured up. The table below shows the total cost of PV system on basis of the intuitive method calculation.

TABLE 10 : COST OF THE PV SYSTEM BASED ON INTUITIVE METHOD

No.	ITEMS	UNIT PRICE (Rs)	QUANTITY	AMOUNT (Rs)
1	PV Module	46/W	1286*103 W	5.9 crore
2	Supporting structure	10/W	1286*103W	1.2 crore
3	Battery	92.77/Ah	357 Ah	33118.89
4	Inverter	120/kW	150 kW	18000
5	Maintenance cost			295000
	TOTAL			7.2 crore

Numerical Method

Using the load demand and solar radiation values, the power of PV module and storage battery capacity is calculated with the help of numerical method. The cost of PV system is figured up using the per unit cost of each component. The table below shows the cost of the entire system using numerical method.

TABLE 11: COST OF THE PV SYSTEM BASED ON NUMERICAL METHOD

No.	ITEMS	UNIT PRICE (Rs)	QUANTITY	AMOUNT (Rs)
1	PV Module	46/W	292*103 W	1.3 crore
2	Supporting structure	10/W	292*103W	29 lakh
3	Battery	92.77/A h	364.58 Ah	33822.09
4	Inverter	120/kW	10 kW	1200
5	Maintenanc e cost			46720
	TOTAL			1.6 crore

On comparing both the numerical and intuitive method, the cost estimation results show that the intuitive method is more expensive than numerical method. It is clear that the availability of the proposed system is higher than the system designed by the intuitive method despite that the storage battery of the first system is much higher than the proposed wordsystem.

V. CONCLUSION

In this research optimal sizing of a standalone PV system for Karunya University, Coimbatore has been done. The optimization was conducted in terms of PV array tilt angle as well as the size of the system's energy sources. Numerical

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methods for optimization of the PV module tilt angle, PV array size and storage battery capacity were implemented using MATLAB and meteorological data of Thondamuthur region and load demand of Computer Technology Centre, Karunya University were used for optimal sizing.
The PV array can be tilted at 30°, 30°, 20° and 20° in every three months to receive maximum global solar energy. Optimization of PV array tilt angle can reduce the number of site visits, minimize shading effect and increase radiation capturing efficiency without any tracking system as it increases the initial cost, losses and maintenance cost.
Based on this result it is proved that the system designed by intuitive method is more expensive than the system designed by the numerical method.

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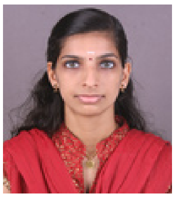

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