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Economic Analysis of Solar PV System using Maximum Power Calculation of a Solar panel

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***Abstract*-- Solar panel maximum power is calculated with the equivalent circuit model in respect to the solar cell. Though different model circuits have been developed, basic practical circuit of a diode with ohmic losses is considered as the shunt resistance is very high and has a little influence in the model. The maximum power calculation is evaluated using mathematical methods and hence set to the further calculation of economic analysis of Solar PV system which includes Life cycle cost analysis, Cost benefit analysis and payback period helps to remain the objective of the paper.**

***Keywords*-- Maximum power, Life cycle cost analysis, Savings, and Payback period.**

I.INTRODUCTION

In today world, demand of electricity has risen such that there is no place without electricity. Generation of power through all sources also rose. Particularly in India, due to crisis of power generation through conventional sources, renewable energy sources like solar plays a helping role. For this, solar photovoltaic technology [5] is the promising renewable technology. This technology arises with the maximum power calculation of the solar panel which has the major contribution. Though there were advances in the circuit construction of solar cell, the practical model with ohmic losses is considered. Maximum power is calculated with the clear cut method and iterative method.

Solar energy is the energy received from the sun in the form of solar radiation. The radiation reaching the earth's atmosphere is called insolation. The average insolation in India is 5kWh/m²/day. The average sun-shine hours in a day is approximately 8 hours. These two data are primarily required to generate the solar power.

The significant factors which contribute the economic evaluation of PV system include the sizing of components, life cycle cost of system and pay back analysis. This paper presents the comprehensive economic analysis [2] of PV system required to install and generate power to meet the load demand.

II. SOLAR PANEL DESIGN

A. Clear cut method:

The equivalent circuit of solar cell with series resistance is shown in fig 1.

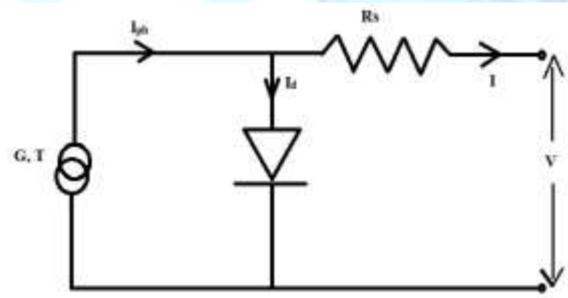

Fig 1: Equivalent circuit of solar cell

Applying KCL to the above circuit, output current I is given in equations (1), (2). I_{ph} is the photo current or light generated current, I_d is the diode current, R_s is the series resistance and V is the output voltage of the solar cell. The three points on the I-V characteristics which are required are: (0, Isc), (Voc, 0) and (Vm, Im) which is shown in fig 2.

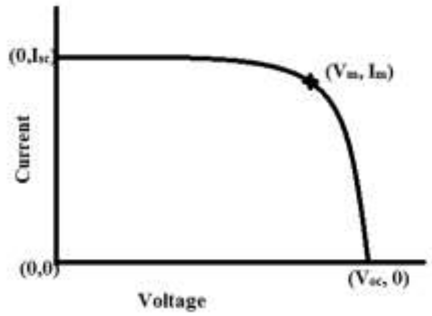

Fig 2: V-I characteristics of solar cell

Where I_{sc} is the short circuit current and V_{oc} is the open circuit voltage of the cell. V_m and I_m are the voltage and current values at the maximum point. These three points shows the graph of maximum power point tracking system of the simplest method. The mathematical model [6] [7] of this system is given below:

Current Equation:

$$I = I_{ph} - I_d \quad (1)$$

i.e.,

$$I = I_{ph} - I_o \left[e^{\left(\frac{q(V+IR_S)}{AKT_j}\right)} - 1 \right] \quad (2)$$

At (0, Isc)

$$I_{sc} = I_{ph} - I_o \left[e^{\left(\frac{qI_{sc}R_S}{AKT_j}\right)} - 1 \right] \quad (3)$$

At (Voc, 0)

$$0 = I_{ph} - I_0 \left[e^{\left(\frac{qV_{oc}}{AKT_j}\right)} - 1 \right] \quad (4)$$

At (Vm, Im)

$$I_m = I_{ph} - I_o \left[e^{\left(\frac{qV_m+I_mR_S}{AKT_j}\right)} - 1 \right] \quad (5)$$

Where q is the charge of electron ($1.6*10^{-19}$ C) and K is Boltzmann constant ($1.38*10^{-23}$ J/K). T_j is the ambient temperature. A is the diode ideality factor ranging between 1 and 2 and including both depending upon the material used. Generally silicon has 1 to 1.5. I_o is the reverse saturation current usually of tiny value. Its value is calculated from (4).

The simplified model is obtained mathematically from above (3), (4) and (5) by neglecting the '-1' term as the exponential term results very high than 1 and the short circuit current is equal to the photo current. The following equations are:

$$I_{ph} = I_{sc} \quad (6)$$

$$I_{ph} = I_o \left[exp\left(\frac{qV_{oc}}{AKT_j}\right) \right] \quad (7)$$

$$I_m = I_{ph} - I_o \left[exp\left(\frac{q(V_m+I_mR_S)}{AKT_j}\right) \right] \quad (8)$$

By substituting the equations (6) (7) (8) in equation (2) the final equation of current is given as

$$I = I_{sc} - I_o \left[exp\left(q\left(\frac{V-V_{oc}+IR_S}{AKT_j}\right) \right) \right] \quad (9)$$

V_{oc} is also said to be the output voltage of the solar cell as it is the maximum voltage. For a single cell it is 0.5 or 0.6 V. For a panel, it is the product of output voltage of a cell and the number of cells in series. As seen, the equation (9) has the output current itself is a function having a nonlinear relation. Hence the maximum power is obtained by differentiating the power with respect to the voltage as in (10).

$$\frac{d(VI)}{dV} = \frac{\partial V}{\partial V} I + \frac{\partial I}{\partial V} V = 0 \quad (10)$$

An alternative method of deriving the maximum power is given with considering the both inputs of irradiation (G) and temperature (T) [7]. The short circuit current and open circuit voltage are given as:

$$I_{sc} = I_{sc,ref} \frac{G}{G_{ref}} + \alpha_{sc}(T_j - T_{j,ref}) \quad (11)$$

$$V_{oc} = V_{oc,ref} + V_t \ln\left(\frac{G}{G_{ref}}\right) + \beta_{oc}(T_j - T_{j,ref}) \quad (12)$$

Where V_t is the thermal voltage of the diode. $V_t = \frac{A.K.T_j}{q}$

The (11) and (12) are dependent on both G and T along with their temperature. The maximum power is derived from product of (11) and (12) by replacing V_{oc}, $V_{oc,ref}$, I_{sc}, $I_{sc,ref}$ by V_m, $V_{m,ref}$, I_m, $I_{m,ref}$.

B. Iterative method:

As seen in above method, the output current is function of itself too. Hence to solve this equation an iterative solution [6, 8] is proposed. Well known Newton Raphson method is used here to find out the output current.

Before to get this current value, the voltage used in the above equation is calculated by using potentiometer. The formula (13) given for the potentiometer is given as

$$V = \frac{R2}{R2+R1} Voc \tag{13}$$

Here R1 is fixed one (100Ω) and R2 is variable one.

The Newton Raphson procedure is given as

The current function (14) and its derivative (15) are:

$$f(I) = N_p I_{ph} - I - N_p I_o \left[e^{q\frac{\left(\frac{V}{N_S}+\frac{R_S I}{N_p}\right)}{AKT_j}} - 1 \right] \tag{14}$$

$$f'(I) = -1 - N_p I_o \left[e^{q\frac{\left(\frac{V}{N_S}+\frac{R_S I}{N_p}\right)}{AKT_j}} \right] \left(\frac{\frac{R_S}{N_p}}{\frac{AKT_j}{q}} \right) \tag{15}$$

$$I_{n+1} = I_n - \left(\frac{f(I)}{f'(I)} \right) \tag{16}$$

The current in (16) is obtained after certain iterations where it is satisfies the convergence value and this current multiplied by the voltage obtained by potentiometer gives the power from the panel. It is observed that there will be a maximum point where the power acquires the maximum value. Corresponding voltage and current values represent their maximum voltage and maximum current at that point.

TABLE I
PV MODULE SPECIFICATIONS

Characteristics	*Rating*
Maximum Power (Pm,ref)	*150W*
Voltage at Pmax (Vm,ref)	*34.5V*
Current at Pmax (Im,ref)	*4.35A*
Short-circuit current (Isc,ref)	*4.75A*
Open-circuit voltage (Voc,ref)	*43.5V*
Area(Am)	*1.2m²*
Efficiency (η)	*15%*
Standard Irradiance (Gref)	*1000 W/m²*
Standard Temperature (Tref)	*25ºC*
Current Temperature Coefficient (α_{sc})	*(0.065±0.015)%/°C*
Voltage Temperature Coefficient (β_{oc})	*– (160±20)mV/°C*
Number of cells in series (Ns)	*72*
Number of cells in parallel	*1*

The maximum power is calculated by above two methods with considering the parameters in table 1. The maximum power obtained is used further in economic analysis of the PV system as explained in detail below.

IV.PV SYSTEM DESIGN

A. *Load Profile:*

Load data is shown in table 2 having the load consumption values of all months in kWh of GITAM College for the year 2013. For further analysis, the monthly data is converted to daily and hourly consumption.

TABLE II
ENERGY CONSUMPTION DATA

Month	Electrical energy consumption, kWh
January	296300
February	390700
March	367900
April	444850
May	323850
June	268450
July	456450
August	460000
September	526750
October	369500

November	482000
December	424400

Economic analysis for the above obtained power values is done by using the sizing of components which are required in Solar PV system.

B. PV array Sizing:
Using the specifications in table 1, the size of the PV modules (N_{PV}) required is given as

$$N_{PV} = \frac{E_{load}}{E/m^2 A_m \eta_m} . factor\ of\ safety \qquad (17)$$

Where
Eload: Average energy consumed by the load per day
Am: Area of PV module
ηm: Average energy received by PV module on a horizontal mode during solar days.
Safety factor in the equation (17) used as a tolerance value usually as 1.2 or 1.3.

C. Battery Sizing:
As battery stores energy, the capacity (18) to store the power not being wasted such as when the panel doesn't work at night times and cloudy days is calculated at first.

$$Storage\ capacity = \frac{N_C E_{load}}{DOD \eta_b} \qquad (18)$$

Where
NC : largest number of continuous cloudy days
DOD: depth of discharge of battery
ηb : efficiency of battery

Assuming the maximum continuous cloudy days as 2 and depth of discharge of 0.8 with 80, the required ampere-hours of the battery (19) and number of batteries (20) are given as,

$$Required\ ah\ of\ battery\ (Ah) = \frac{Storage\ capatiy}{DC\ Bus\ voltage} \qquad (19)$$

The DC bus voltage is taken as 96 V and the number of batteries (N_b) is given as,

$$N_b = \frac{Ah}{Battery\ ampere\ hour} \qquad (20)$$

D. MPPT Controller Sizing:
Sizing of controllers (21) is calculated such that the output voltage of controller is equal to the nominal battery voltage and input voltage should be greater than the maximum PV voltage .

$$N_C = \frac{P_{maxtot}\ of\ PV}{P_{max_{controller}}} \qquad (21)$$

Where P_{maxtot} of PV = P_{max} . NPV
$P_{maxcontroller}$ = Vb . $I_{controller}$

Where V_b = Voltage of battery bank, $I_{controller}$ = current of controller, 80 Amps.

E. Sizing of Inverter:
Sizing of inverter (N_i) in (22) is given as

$$N_i = \frac{req\ rated\ o/p\ power\ of\ inverter}{inverter\ rated\ power} \qquad (22)$$

Where required rated output power is equal to 125% of load (kWh/hr) and inverter rated power is taken from inverter specification. The inverter specifications are with 2250 W, 96 V DC, 220 V AC and 50 Hz.

V. ECONOMIC ANALYSIS

A. Life Cycle Cost Analysis:
Life Cycle Cost method is the only method which includes all the costs like instalment cost, operating cost, maintenance cost and replacement cost. This method implies the economic analysis to be precise. The total life time (N) of the system is considered for 20 years. As the batteries cannot withstand the whole life time, they are replaced for every 5 years i.e. after 5 years, 10 years and 15 years [1, 2].
Inflation rate (i) and discount rate (d) assumed as 3 and 9 % as they are considered for any project analysis. Below table represents the cost data of PV system components.

TABLE III
COST DATA OF PV SYSTEM COMPONENTS

Item	*Cost*
PV module	*36 Rs/WP*
Battery	*6 Rs/Ah*
MPPT Charger	*35.27 Rs/A*

Load (kWh)	Conventional generation cost (Rs)	Integrated Solar PV generation cost (Rs)
556	28866900	4.4786e+007
	38489200	59714400
	48111500	74643000
278	28866900	2.2393e+007
	38489200	29857200
	48111500	37321500
140	28866900	11277000
	38489200	15036000
	48111500	18795000

Inverter	*6 Rs/W*
Installation	*10% of PV Cost*
O&M/yr	*2% of PV Cost*

Using Table 3, the cost of the different components are given as follows:

PV array cost (C_{PV}) = (Cost of PV module/W)*(N_{PV})*P_m
As seen, in above formula, the maximum power obtained above is used to calculate the cost of the PV array.

Initial cost of batteries (C_b) = (Battery Cost/Ah)*(Ah)

Extra group of batteries (C_{bn}) = $C_b*(\frac{1+i}{1+d})^N$

Controller Cost ($C_{controller}$) = (Cost of controller/A)*(Maximum current of controller)*NC

Inverter Cost (C_{inv}) = (Cost of Inverter/W)*(inverter rated power)*Ni

Installation Cost (C_{inst}) = (Cost of Installation)*(PV array cost)

Maintenance Cost (C_m) = $\frac{M}{yr}\left(\frac{1+i}{1+d}\right)\left[\frac{1-\left(\frac{1+i}{1+d}\right)^N}{1-\left(\frac{1+i}{1+d}\right)}\right]$

Life cycle cost (LCC) = C_{PV} + C_b + C_{bn} + $C_{controller}$ + C_{inv} + C_{inst} + C_m

Annualized LCC (ALCC) = LCC $\left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^N}\right]$

Unit Electrical Cost (UEC) = $\frac{ALCC}{365*E_{load}}$

From all the above formulas, we get the Life Cycle Cost and Unit Electrical Cost (UEC) of solar energy generated.

A. *B. Cost-Benefit Analysis:*

Cost benefit analysis are the savings occurred from the cost of generation of solar power to the cost of electricity from the grid. These values depend on the generation of solar power. If any excess power is generated, then the electricity bill incurred itself becomes the savings.

C. Payback Analysis:

The expected time taken in years for the investment to be returned is called payback period (23).

$$Pay\ back\ period = \frac{LCC}{Annual\ Savings} \quad (23)$$

VI Analysis of Results

From the results obtained, as seen in table 4, the maximum power obtained from both methods are same value i.e 150 W equal to the reference value. The later method is widely used as the iterations gives the optimal value, though the first method had the direct equations to get the maximum power. If a solar system is installed in a system there will be cost savings at the load stations. The installation cost may be high at the initial point but from the result we can calculate the payback period and from there onwards there may be no need to pay any amount to the grid system. In this paper, the user interface is developed usually called as the GUI model, can be used for any load system. The detailed analysis of savings is shown in table 5,6,7.

TABLE IV
CALCULATION OF MAXIMUM POWER

Parameter	Clear-cut Method	Iterative Method
Open circuit Voltage (V_{oc})	34.7 V	17.02 A
Short circuit Current (I_{sc})	4.32 V	15.75 A
Maximum Power ($P_m = V_m * I_m$)	150.62 W	268.08 W

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TABLE V
COMPARISION OF COSTS BETWEEN CONVENTIONAL AND INTEGRATED SOLAR PV GENERATION

When Unit Electrical Cost (UEC) is considered for Integrated Solar PV generation, it is seen that the cost of the integrated Solar PV is less than the conventional generation which implies the savings are more. From the analysis the UEC obtained is 2.37 Rs. The full details are shown in table 6.

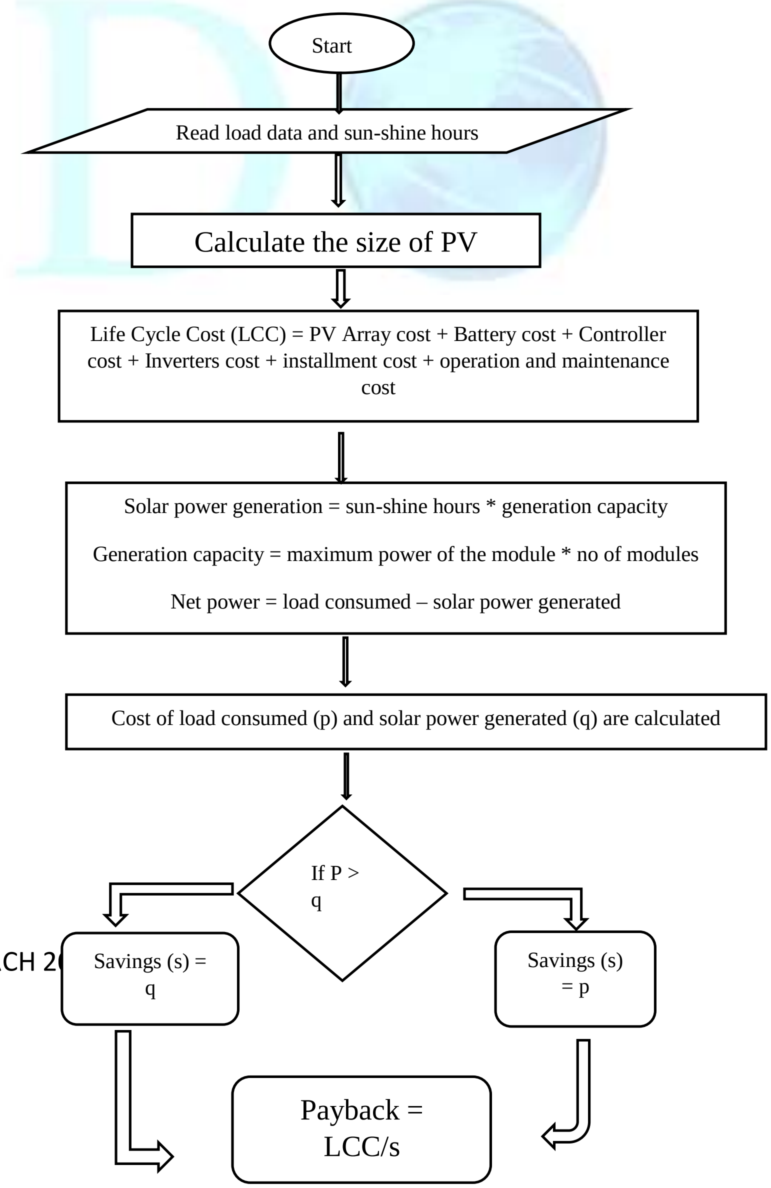
TABLE VI
COMPARISION WHEN SOLAR UEC IS TAKEN INTO CONSIDERATION

Load (kWh)	Conventional generation cost (Rs) with different unit cost.		Integrated Solar PV generation cost (Rs) with UEC
556	6	28866900	1.7781e+007
	8	38489200	1.7781e+007
	10	48111500	1.7781e+007
278	6	28866900	8.8504e+006
	8	38489200	8.8504e+006
	10	48111500	8.8504e+006
140	6	28866900	4.4470e+006
	8	38489200	4.4470e+006
	10	48111500	4.4470e+006

TABLE VII
SAVINGS AND PAYBACK PERIOD FOR DIFFERENT LOADS AND GRID COST

Cost per unit		Load= 556 kWh	Load=278 kWh	Load=140 kWh
	LCC (Rs)	143060000	71308000	35931000
6	Savings (Rs)	44850240	22457000	11341000
	Payback (years)	4.9	3.2	3
8	Savings (Rs)	59800320	29943000	15121920
	Payback (years)	3.7	2.5	2.3
10	Savings (Rs)	74750400	37429000	18902400
	Payback (years)	2.9	2	1.9

VII. FLOW CHART OF ECONOMIC ANALYSIS



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This paper presents the economic analysis of PV system for a certain load with the maximum power calculation. It is seen that in both methods, the maximum power is obtained is same. The iterative method evaluation is done so that the accuracy is obtained more. The life cycle cost and payback period for the required load has been calculated and analyzed. It is seen that unit electrical cost of PV is also feasible. Though the payback analysis of different loads gives the same value for a particular grid cost, the investment factor plays the key role depending on future savings. By the Graphical User Interface in MATLAB, it is feasible for the consumer to get awareness about the installation of PV systems.

VII GUI APPROACH

The above cost analysis of proposed Solar system is accosted in Graphical Interface in MATLAB. The interface with input data elements to be given are represented in fig 6.

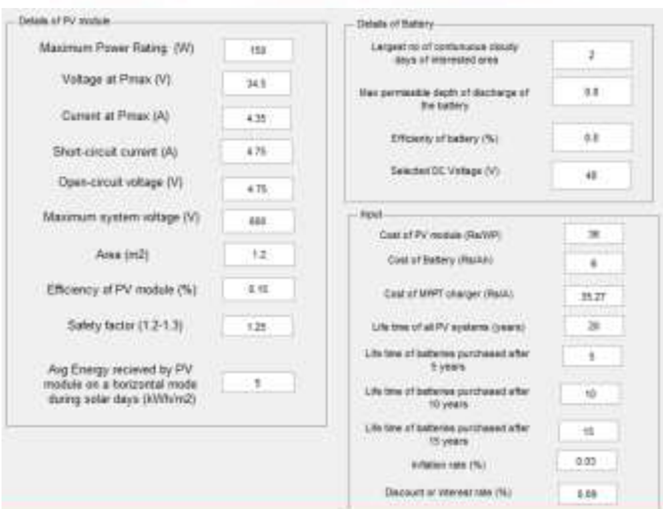

Fig 6: Input Parameters for Economic Analysis of Solar PV System

VIII CONCLUSIONS

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