Simulation analysis of Shadow Factor and unit cost in the booster mirror arrangement for a solar panel

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Abstract — A simulation and experimental study was attempted to increase the power output from a 75 W mono and multi crystalline solar panel using V Trough solar concentrators, thus estimating its ideal concentration ratio for domestic applications in the absence of automatic tracking. The net radiation falling on the panel due to reflection from concentrators and the shading caused by the reflectors was simulated using TRACE PRO and PV Syst Software, calculating the net power output, losses and output energy. Through the simulated values, the calculated unit cost of energy for the concentrator arrangement with 1 X, 2 X, 3 X and 4 X configurations are found to be 0.81, 0.70, 0.74 and 0.75 $/kWh respectively for the 1st year. It is estimated that 2 X configuration having a surface temperature of less than 70°C, CO_2 savings of 28 % higher than the reference model and a unit cost of 0.7 $/kWh is the optimum concentration ratio for a solar V Trough concentrator.

Keywords— Booster mirror, V Trough, Shadow Factor, PV SYST, Trace Pro, CO_2 emission.

I. INTRODUCTION

The limitation in the conversion efficiency of the solar panel has led to the study of solar concentrators which helps to increase the amount of incoming radiation falling on the solar panel. Depending on the concentrator configuration, it is categorized as LCPV, whose concentration ratio ranges between 1 X to 10 X or HCPV, whose concentration ratio ranges between 10 X to 1000 X. Booster mirror or V Trough is a LCPV with concentration ratios ranging from 1 X to 4 X [1, 2] where tracking of the setup becomes necessary due to the effects of shading.

In the absence of tracking, the concentrator arrangement will impose a shadow on the solar panel, known as shadow factor. A solar panel without any active shadow falling on it will have a shadow factor of 1 and a completely shadowed panel will have a factor as 0. The amount of shading developed on the solar panel depends on the size of the reflector, the sun angle and the trough angle [3, 4].

The shadow analysis is done by using PV SYST which is photovoltaic modelling software through which PV off grid and on grid systems can be designed. Also the shadow falling on a photovoltaic panel can be analysed through the tool called "Near Shadings and Perspective".

Nomenclature

W	Peak watt rating of the panel at Standard Test Conditions (STC)	Γ	Surface azimuth angle
X	Concentration ratio	ψ	Trough angle
kWh	1 unit of electrical energy output	$R_1, R_2, R_3, R4$	Aluminium reflectors
α	Acceptance angle of the light rays on the reflector		Tilt angle of the panel
CR	Concentration Ratio	BOS	Balance of system including battery, wiring and inverters
$LCPV$	Low Concentrated Photovoltaics	$HCPV$	High Concentrated Photovoltaics

Note: 1 $ is assumed as Rs.55

Equations to determine the concentration ratio and the size of the reflector depends on the angle of the acceptance of light rays 'α' and trough angle 'ψ' [4]. The dimensions of the reflector computed using these equations, are fed to the PV SYST software and the simulations are run for computing the shadow factor and the net power. The presence of concentrator model has an increasing effect on temperature of the panel due to additional radiation falling on it, thereby making it necessary to choose an optimum concentration ratio for V Trough concentrator [5].

Trace Pro, an optical modelling software is used for analysing the reflection of the light rays from the booster mirror by configuring the reflector dimensions, reflectivity of the material and the absorptivity of the panel [6]. The absorptivity of the material in the Trace Pro simulation is chosen as 15 % so as to match the electrical conversion efficiency of the solar panel. The illumination source was also added to the system with visible and IR radiation properties similar to the sun's radiation spectrum.

Due to increased output from the V Trough concentrator, the CO_2 emission free energy generated is increased and the carbon emissions savings is calculated in the model. A case study at the Fiera Di Roma plant at Italy showed that the 1 MW can prevent 262 tonnes of CO_2 per year [7]. A similar scale is used in the paper to estimate the amount of CO_2 emission prevention.

In this paper, the modelling of booster mirror technology using simulation software is explained. The work done in the paper is

- Analysis of concentration density with flat mirrors – Mathematical and simulation approach
- Ray Trace study using Trace Pro for different concentration ratios of the booster mirror.
- Experimental analysis of the system
- The cost of construction of the respective model is also evaluated.
- A Cost/Unit and temperature study is done to find the effective booster mirror model.
- Prevention of CO_2emission in the environment.

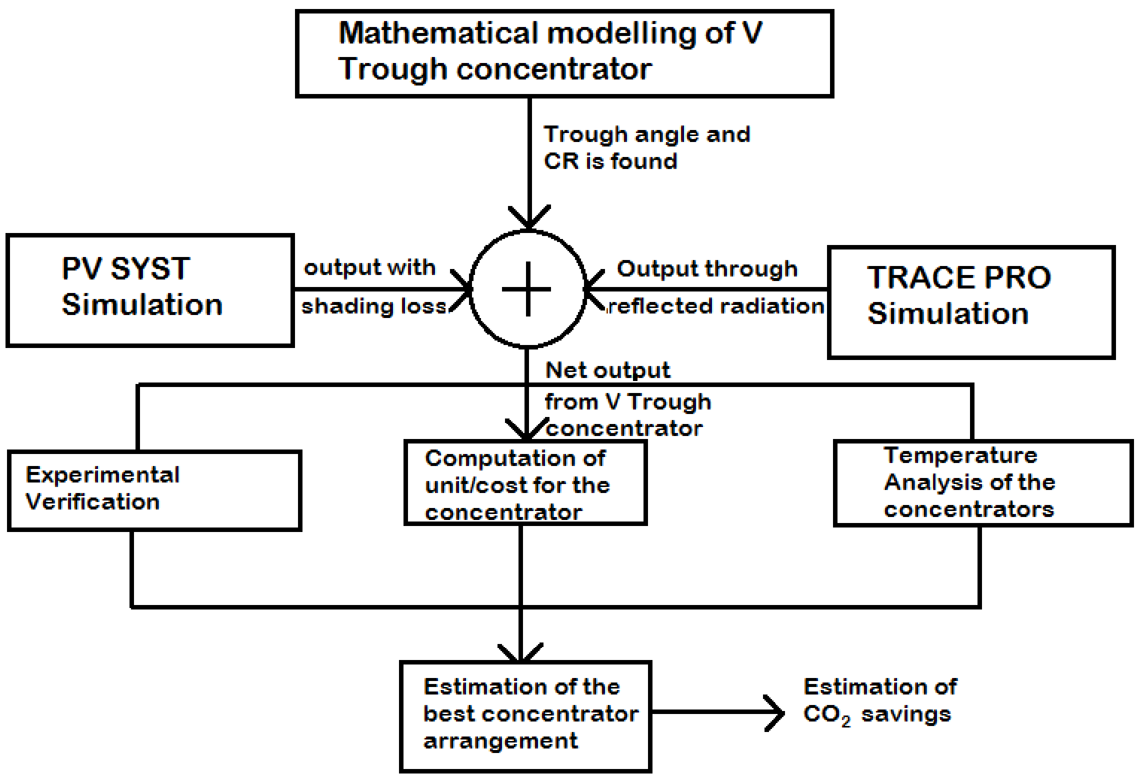

Fig.1. Flow chart to estimate optimum concentrator model

The flowchart to estimate the optimum concentration ratio is explained in figure 1. The optimum concentration ratio, trough angle and the concentrator dimensions are calculated using mathematical equation and are fed to the simulation software to analyse the shading loss and calculate reflected power. The sum of the total power obtained from Trace Pro simulations and power obtained after considering the shading losses in PV Syst is the net simulated power obtained in the booster mirror system. The net power and energy output for 1 X, 2 X, 3 X and 4 X concentrators are found and experimentally validated using a concentrator setup. Temperature study is done to restrict the CR's for V Trough and unit / cost ratio is found to estimate the best CR for a V Trough concentrator, for which the net CO_2 savings is found.

II. CALCULATED ANALYSIS OF CONCENTRATION DENSITY WITH FLAT MIRRORS

2.1 *Estimation of net concentration density through mathematical analysis*

The net concentration density is found by mathematical relationship and then validated by simulation for which either the geometrical concentration ratio or optical concentration ratio is taken. For V Trough concentrators the mirror area required for 2 X optical concentration is higher than that of 2 X geometrical concentration. For this work, the geometrical concentration is taken into effect. When the reflectors are kept 120° with respect to the panel, maximum concentration is observed. Also, through seasonal tracking the panels will always be faced towards the sun so that the concentration ratio is maintained. A relationship between the geometrical and optical concentration ratio is also formulated and is used for analysis in this paper. Optical concentration ratio [4] can be given as

$$\mathbf{CR = \sin((2n+1)(\alpha-90)) / \sin(\alpha - 90)} \qquad \textbf{(1)}$$

Where, n is the number of reflectors and (α-90), also represented as ψ is the trough angle. In this case, α = 120 degrees which is mentioned above. For the chosen geometrical concentration 2 X model in the paper, optical concentration ratio is 1 X. The same condition will be analysed using PV SYST software and Trace Pro.

2.2 PV SYST simulation

2.2.1 *System Considered for Simulation*

A 75 W multi crystalline solar panel is taken for this simulation study. Four reflectors R1, R2, R3 and R4 are taken which are fixed to the solar panel. Fig.2. shows the representation of the panel with booster mirror concentrators in PV SYST where the panel is kept at an angle γ with respect to the NS –EW lines. The booster mirror structures are elevated at an angle through the "object positioning tool" which is present in the software.

A tool "Shadings and Perspective" is available in the PV SYST software through which any shading scenario can be created and its effect on the performance on an active PV panel can be evaluated. The booster mirror model is considered for various concentration levels and its design should be in such a way to minimize the shading losses and to increase the amount of radiation falling on to the panel. The dimensions of the concentrator and panel are given in Table 1.

Table.1
Sizing of the reflector arrangement

System	Area (in m^2)			
Solar PV panel	0.656 * 0.88			
Concentration ratio	1 X	2 X	3 X	4 X
Reflector R1, R3	0.33	0.33	0.66	0.66
Reflectors R2, R4	0.22	0.44	0.44	0.88

Fig.2 shows the PV SYST design concentration model. The tool is similar to a CAD design and the scenario is created for the given specifications of the solar panel and the reflectors.

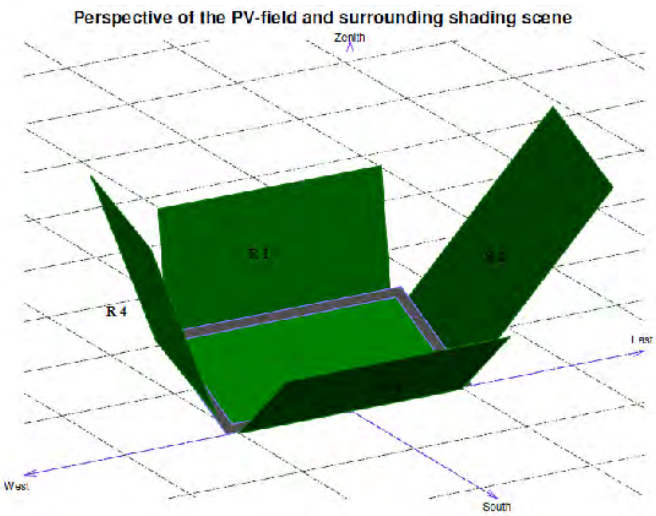

Fig.2. Simulation of a V Trough concentrator

Shading factor is computed for the specific models and the net energy obtained due to the shading factor is also calculated. Table 2 shows the comparison of different concentrations, their shading factors and the respective power output obtained.

The crystalline panel with the following specification is chosen for the simulation analysis.

- Panel type : Polycrystalline silicon
- Panel area : 0.58 m^2
- Total power : 75 W
- Tilt : 11 ^{0}
- Location : Chennai
- Panel dimensions : 0.656 * 0.88 m

2.2.2 *Analysis of results*

Table2
Shading factor analysis using PV Syst

System	1 X	2 X	3 X	4 X	Without concentration
Shading factor	0.91	0.84	0.75	0.72	1.00
$E_{shading}$	98	91	81	77	108

Where,

$E_{shading}$ - Net energy after shading losses (kWh/Year)

The table depicts that the shadow factor of the system increases with increase in concentration ratio, revealing the extent up to which the system loses power due to the effect of shading by the booster mirrors. The PV Syst simulation result gives the net power output from the concentrator arrangement.

The software computes the total power that can be generated for a year using the given specifications of the panel. As shown in Table 2, the 75 W model generates 108 kWh per year without any concentration. Due to shading losses, a 1 X concentrator model generates 98 units. The energy generation decreases as the concentration ratio increases due to the effect of shading.

III. COMPUTATION OF NET RADIATION DUE TO REFLECTANCE BY TRACE PRO SIMULATION

3.1 *System Considered for Simulation*

Trace Pro is an optical modelling software through which the total radiation falling on the system can be computed. The following parameters are fixed during the simulation.

- Concentrator material – Glass with reflectance as **0.95**
- Material of the panel – Absorber with 15 percent efficiency (Similar to solar panel)
- Input power – 1000 W/m^2 light source
- Wavelength – 0.5461 µm (Visible)
- Beam status – Uniform

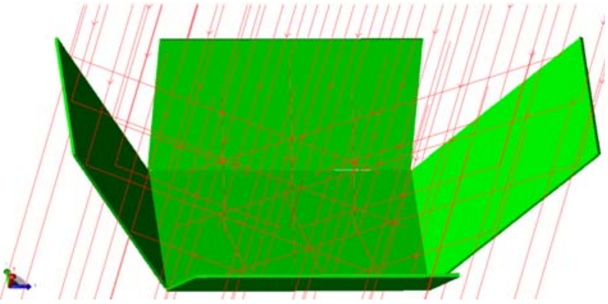

Fig.3. Trace Pro Model and ray Trace Analysis of a 4 X Concentrator

Fig.3 shows the booster mirror model and its ray trace diagram using the Trace Pro software. The net effective solar radiation falling on the absorber can be found. The receiver plate at the centre is configured for 15 % absorption so that it works similar to a solar panel. The following results are obtained by considering the reflector material as glass. The trough angles are configured from the mathematical values derived earlier

3.2 *Analysis of results*

Table 3
Output energy analysis in Trace Pro

System	1 X	2 X	3 X	4 X
Reflected power (Watts)	20	50	64	80
Final absorbed power after losses (Watts)	18	45	57	70
Net energy in a year (kWh /Year) *	27	66	84	102

* 320 sunny days are assumed for the simulation

Table 3 shows the power obtained in the system due to reflection of the booster mirror. Optical and heat losses are considered in the Trace Pro model which is deducted from the obtained power for an entire year.

The algebraic sum of the energy obtained from the Trace Pro simulation and the energy obtained after deducting the shadow losses in PV Syst will gives the net output energy. Table 4 shows that the net energy increases with increase in concentration ratio. It is evident that the net power output from a solar panel deploying concentrator is high.

Table 4
Computation of net energy

System	Net energy (kWh/Year)
No conc	108
1 X	125
2 X	157
3 X	165
4 X	179

IV. STUDY OF TEMPERATURE IN THE SYSTEM

4.1 Temperature dependence of the system

Due to the increased radiation falling on the panel, the net component temperature increases with the increase in concentration ratio. A concentration test was done on a solar panel using a V Trough concentrator. The following were observed during testing.

- Radiation – 850 W/m^2
- Wind Speed – 7 km/hr
- Location – Chennai

Table 5 shows the results obtained after keeping the panel for duration of 10 minutes under the fore mentioned conditions. The temperature of the panel was measured using a thermal imaging camera.

Table.5
Temperature rise in modules by concentration

System	Front surface temperature (^{0}C)	Back surface temperature (^{0}C)
Without concentration	51	50
1 X	56	58
2 X	70	71
3 X	75	77
4 X	85	88

4.2 Analysis of results

Table 5 shows that the temperature of the panel tends to increase to 75^0C when the panel is illuminated to 3 X concentration. This will have adverse effects on the panel's performance. It might also permanently damage the solar panel. Also the power - temperature of the panel is – 0.47 %/k. Thus, an increase in temperature to more than 75^0C will see a drop of 35 % in the power.

V. ESTIMATION OF COST

5.1 Cost Evaluation of the System

The following costs are fixed for the construction of the equipment based on the market values,

- Cost of multi crystalline panel of 75 Wp – 0.5 $/Wp = 37.5 $
- Cost of glass of thickness 2 mm (Reflector) – 5 $ / CR
- Cost of other BOS – 30 $
- Cost of Fabrication, seasonal tilting and other accessories – 20 $

The total cost of the system can be computed by the above factors. As the concentration ratio increases the cost of glass and the fabrication alone will increase. Only the first year's unit energy cost is taken into consideration here.

Table 6
Calculation of Cost/Unit

System	Cost of the System (in $)	Net Energy (kWh/Year)	Cost/Unit $ / (kWh/Year)
No Concentration	92.5	108	0.92
1 X	102	125	0.81
2 X	110	157	0.70
3 X	122	165	0.74
4 X	135	179	0.75

5.2 Analysis of results

Table 6 explains the Cost/Unit ratio of the booster mirror models. It is evident that the trend of the Cost/Unit ratio decreases till 2 X level and increases after that. This is due to the high optical, shadow and heat losses in the system. Moreover, a single junction mono crystalline panel will not withstand concentrator levels beyond 3 X, thereby eliminating the possibility to use them. When the Levelized cost is calculated for 25 years there will be a further decrease in price of 2 X concentrator's energy. When compared to reference solar panel, the 2 X concentrator offers energy at a 31% declined price.

VI. EXPERIMENTAL INVESTIGATION OF THE SYSTEM

6.1 *Experimental Setup*

A V trough concentrator prototype was made for concentration ratios of 1 X and 2 X to experimentally validate the simulation results. The panel was rated at 75 Wp. The setup was kept at Chennai and the experiment was conducted for 6 months duration during December to May

Fig.4. 1 X and 2 X concentration arrangement

Fig.4. shows the glass concentrator arrangement with 2 X configuration of reflectivity 0.9 which was used for the experimentation. Table 7 explains the experimental validation obtained from a 75 W panel.

Table 7
Experimental validation in 75 W panel

S.No	Concentration ratio	Maximum recorded power (Pmpp) at site (Watts)	Average units / day (kWh / day)	Actual Average units / year (kWh / Year)	Simulated value (kWh/Year)	% Deviation
1	No concentration	55	0.33	105.6	108	2.27
2	1 X	60	0.36	115.2	125	8.5
3	2 X	75	0.45	144	157	9.02

6.2 Analysis of results

The values obtained in table 7 support the simulation results obtained in table 4. Through the experimental analysis it is noted that the 75 W panel yields 10 units per month and thus about 110 units per year. The deviation for the simulated and the actual values arise due to the temperature rise in the panel and various other environmental parameters like dust and wind.

VII. IMPACT ON ENVIRONMENT

The usage of conventional energy resources lead to release of CO_2 in the environment, making the production of energy through solar panel necessary to prevent further emission of CO_2. For this estimation, the amount of CO_2 released due to production of glass, solar cells and other components is also computed. The study on the previous installed Solar PV plants indicates that a 1 MW plant can replace 260 tonnes of CO_2 per year where the solar panel has an output degradation of 1% for the first 10 years and 0.66 % for the next years after that.

Table 7
Experimental validation in 75 W panel

Type of Setup	CO_2 prevention by energy (In Kg)	CO_2 emission from glass (In Kg)	CO_2 emission from structure manufacturing (In Kg)	CO_2 emission from BOS (In Kg)	CO_2 emission from solar panel manufacturing (In Kg)	Net CO_2 emission prevented for 20 years (In Kg)
Reference Panel (No concentration)	355	0	5	10	92.8	247.2
1 X concentrator	411	4.6	6.5	10	92.8	297.1
2 X concentrator	516	9.2	7.5	10	92.8	396.5

The spilt up of CO_2 emissions and the prevented emission due to energy production from solar is discussed in table 7. The increased energy generation from 1 X and 2 X concentrator aids in the CO_2 savings accordingly. When compared to the reference panel, 1 X and 2 X concentrators have a CO_2 savings of 20.1% and 60.3 % respectively, increasing the importance of using concentrators for solar panels.

VIII. IMPORTANCE OF THE WORK

To achieve grid parity, the mix of solar is very essential along with the conventional energy sources. A 1 kW solar costing 2700 $ can only yield 4 units per day due to its efficiency limitation of 15 % compared to Multi

Junction concentrators with efficiency of 35 %, though its economics is still high, stating the importance of the usage of concentrators. The cost of concentrator arrangement for HCPV ranges from 3 to 4 $ / Watt, compared to 0.7 $ normal crystalline panel. An efficient and cost effective solar concentrator for module level concentration is required, making the V Trough concentrator an excellent choice.

However, an efficient concentration ratio for the V Trough concentrator needs to be obtained. Through mathematical modelling, the concentrator dimensions and trough angles are found which are fed to the PV SYST and Trace pro simulation Softwares. The net energy obtained from these packages gives the output from the concentrator. An experimental validation is also done and cost / unit is evaluated, suggesting that 2 X is the best configuration for a V Trough concentrator whose net CO_2 reduction is also found.

IX. CONCLUSION

It is observed from the simulations and the experimental analysis that 2 X concentrator with unit rate of 0.7 $/unit can be used as the V Trough concentrator for Low Concentrated Photovoltaics. The main advantage of this concentrator model is that it works during diffuse radiation conditions also, since the panel directly faces the sun unlike others concentrator techniques like Cassegrain and Fresnel lens models where the lens is placed between the cell and the sun's path. The performance of the concentrator can be further increased by adopting passive cooling techniques to reduce the surface temperature from 70°C for 2 X concentrator. The booster mirror model was designed using PV Syst and Trace pro softwares for estimating the net energy output for various concentrator configurations, along with the shading and temperature loss. 2 X concentrator with 0.7$/unit with a CO_2 emission saving of 396.5 kgs during its entire lifetime, which is 60.3% more than the normal panel's CO_2 savings was chosen as the best concentrator ratio for V Trough concentrators.

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