A STUDY OF CPV POTENTIAL IN INDIA

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ABSTRACT

This paper attempts to identify the regions in India that are suitable for Concentrated PV (CPV) applications. Technical advantage of a CPV system is compared against its competitor, non-concentrating tracked PV and fixed tilt angle PV systems. Satellite based databases are used for obtaining solar radiation data at 106 locations in India. Hourly radiation values were used for calculating annual output from these technologies. Ambient temperature effects on PV performance were also considered in the evaluation. DNI radiation ratio and diffuse radiation ratio parameters were used to identify regions suitable for CPV and PV. Based on the existing nominal system level conversion efficiency values, CPV systems provided higher output for all regions in India compared to a tracked PV system and a fixed angle tilted PV system. A cut off value of radiation ratio has been defined beyond which benefit of a CPV system vanishes irrespective of its higher conversion efficiency. Cut off diffuse radiation ratio was found to be 0.6 and DNI ratio was found to be 0.55. This could be used a first cut criteria for deciding a region for its suitability for installing a CPV system. Due to the uncertainty in solar radiation values, a sensitivity analysis of output also has been carried out for these locations.

Keywords: Solar potential; India; CPV; Tracked PV; solar radiation database; DNI; GHI; diffuse radiation ratio;

1. INTRODUCTION

Commercial scale power generation using solar photovoltaics (PV) has been carried out successfully for the past few decades. Single junction polysilicon PV modules still dominate the market share providing solar to electrical conversion efficiency in the range of 13 – 17% [1] . Concentrated Photo Voltaics (CPV) is seen as a promising advancement of solar to electrical energy conversion due to their potential to reach higher conversion efficiencies and promise of lower system cost. CPV uses optical concentrators to focus incident radiation onto multijunction solar cells. Multijunction solar cells have higher theoretical limit of conversion efficiency compared to single junction cells [2]. Conversion efficiencies of more than 40% in concentrated light in lab conditions have been demonstrated. Although these cells are much expensive than single junction cells, optical concentration leads to reduced cell area that results in overall reduction in the cost of the system to provide same amount of electrical energy.

Solar flux density (G) reaching a horizontal surface in earth consists of a direct component that reaches the surface directly from Sun (G_{bn}) and a diffuse component (G_d) that is mostly due to scattering in the atmosphere. The relationship between beam horizontal irradiance (G_b) and other components is given by :

$$G_b = G - G_d \quad \text{(eq.1)}$$

Commonly available radiation data can be classified as: global horizontal irradiation (H), diffuse horizontal irradiation (H_d), beam horizontal irradiation (H_b) and beam normal irradiation (H_{bn}). Global horizontal irradiation and the beam (direct) normal irradiation often are referred to as GHI and DNI, respectively. Solar PV technologies target conversion of GHI into electricity whereas concentrating thermal and concentrating PV technologies utilize DNI. To utilize the DNI on a continuous basis, concentrated solar systems are tracked to follow the motion of Sun and it is expected that their benefits will be greater when installed in regions that have high DNI and low cloud cover. During pre feasibility study of solar power generation project evaluation, given site is assessed for potential energy yields based on technology choices. For this analysis, the parameters that influence the performance of the system namely GHI, DNI, diffuse radiation and meteorological parameters such as ambient temperature and wind velocity are required.

It is a normal practice to identify regions that have greater than 2000 kWh/m^2/year (or 5.5 kWh/m^2/day) beam radiation as suitable for concentrating solar technologies [4-6]. Analysis of global potential of concentrating solar technologies indicates that the Middle East & North Africa (MENA) region, southwest USA, southern Europe, parts of South America and many parts of Asia including regions in India and China have high solar potential. Satellite based DNI map of India from SWERA [7] reveals that north western state of Rajasthan and Himalayan region of Ladak have high DNI values that are beneficial for CPV systems. A recent study on Concentrated Solar thermal Power (CSP) potential for India [8] indicates locations in Rajasthan, Gujarat, Madhya Pradesh and Leh region in Kashmir have opportunity for large implementation of CSP systems. However, it is not clear what the potential is for CPV in India. It is necessary to understand, if there is a performance advantage of installing CPV in parts of India that have moderate DNI. In this paper, technical suitability of CPV for regions in India is evaluated. Benefit of CPV for a given location can be accessed only by comparing its competitor, non-concentrated PV technology. PV based power plants normally have panels positioned at a fixed tilt angle. It is possible to increase the incident radiation on these panels by tracking the Sun. Suitability of a given region for CPV and tracked PV have been accessed in this paper considering radiation data and weather parameters. Due to the low market penetration and operational experience with CPV systems, it is not possible to comment on the prices of these systems to carry out an economic evaluation. Hence any comment on economics of power generation for a given site using these technologies has been avoided.

2. METHODOLOGY

2.1 Solar radiation data

Solar radiation data can be obtained by ground measurements, analysis of satellite based data or using models that are derived using other meteorological parameters.

Ground measurements: Solar radiation measurement stations are the primary source of solar radiation data. These measurement stations provide continuous data on a long term basis that are normally used to validate satellite based data. Localized nature of these measurements necessitates installation of this equipment at various places to obtain high spatial resolution. However, it is noticed that many countries do not have high spatial resolution of ground measurements due to the high cost of equipment and the maintenance needed to obtain accurate data. For example, in India, the Indian Meteorological Department (IMD) measures GHI data at 45 stations whereas DNI is measured at very few locations [9]. Hence in places where there are no measurements done, solar radiation can be obtained either by satellite data and using solar radiation models.

Satellite based databases: Weather satellites put into Earth's orbit provide extraterrestrial radiation data and climatic parameters on Earth's surface such as temperature, cloud cover, water vapor, aerosol distribution in the form of maps. The radiation data on Earth's surface is estimated using the extraterrestrial data and other model based calculations using the climatic parameters. The solar radiation data obtained from satellites and estimated using climatic models is maintained as database. In this paper, satellite based data from SWERA database has been used. A brief description of this database is provided here.

The SWERA database is managed by the United Nations Environment Program's (UNEP). The database consists of data for GHI, DNI, latitude tilted irradiation and weather data namely wind, air temperature. SWERA database is a collection of data with different resolutions from different sources such as NASA, NREL, DLR, and SUNY. NASA provides a low resolution pertaining to 1^0 resolution of latitude and longitude, NREL database has moderate resolution data valid for 40km range. SUNY and DLR provide high resolution data from satellite data and derived models with a resolution of 10 km. Details about the methodology used for estimation of data can be obtained from the SWERA website [7].

A combination of satellite based estimates and ground measurements are normally used to get best estimates of solar radiation for a given site.

Model based calculations: Estimation of solar radiation data using meteorological parameters is another approach to obtain solar radiation information for a given location. Models based on parameters such as sunshine hours, clearness index provide information about direct radiation and diffuse radiation with reasonable accuracy under clear sky conditions.

Time resolution of radiation data: Solar radiation data obtained through above methods may be available at high time resolutions (minutes interval) or integrated over different time periods to hourly, daily, monthly or annual values.

2.2 Solar radiation data sources for India

Location of India is to the North of the equator and the tropic of cancer passes through the county. The latitude range is between 8°4' N and 37°6' N and longitude range from 68°7'E and 97°25'E. Recently the Ministry of New and Renewable Energy (MNRE) of Indian Government published global and diffuse data for 16 locations in India from 1986-2000 in the Solar Radiation Handbook [10]**.** Solar radiation data taken from tools such as Meteonorm is published by I.Purohit and P.Purohit [8] for close to 60 India locations**.** Thus it is clear that one has to depend on satellite based information to obtain radiation data that is representative of entire country.

106 locations across India were chosen covering entire latitude and longitude range that incorporates all climatic zones. Figure 1 gives a pictorial representation plot of the selected locations in India for this analysis. A comparison of network of these grid points with map of India (obtained from Survey of India, Government of India) shows that chosen points very well represent Indian geography.

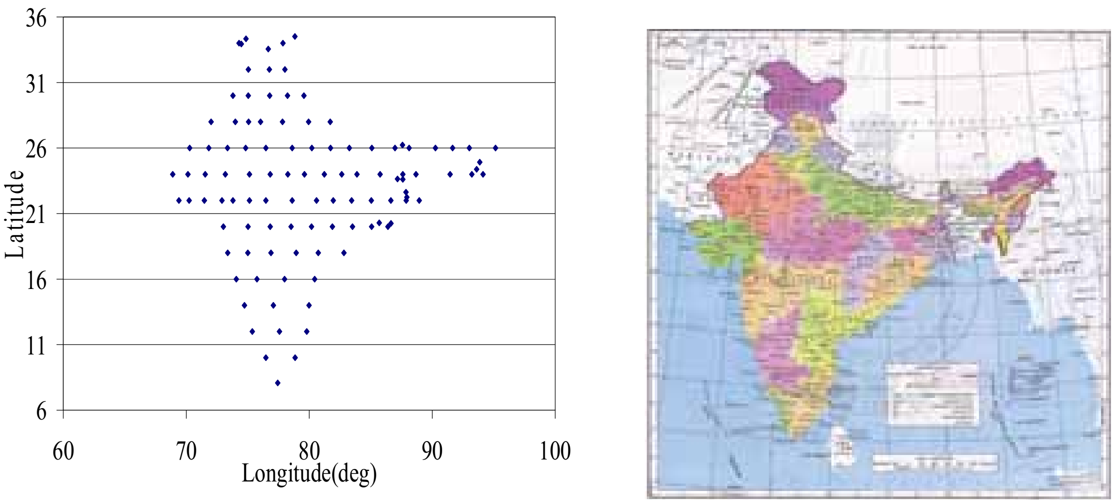

Fig. 1: Selected locations in India (left) and map of India (right)

SWERA database contains low resolution NASA and moderate resolution NREL datasets for all locations in India whereas high resolution SUNY and DLR data is available for only select locations. All radiation databases available for a given location was averaged and used for subsequent analysis. The SWERA database does not provide diffuse radiation data for any locations. Hence it is necessary to compute diffuse radiation. Provided DNI and GHI for a location is known, it is possible to compute daily values of diffuse radiation using equation 1. Instantaneous values of zenith angle at any location is given by

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \qquad \text{(eq.2)}$$

Assuming constant declination for a given day, daily average value of zenith angle is obtained by integrating the hour angle from sunrise to sunset as,

$$\theta_{z,day} = \frac{1}{2\omega_s}\int_{\omega_{sr}}^{\omega_{ss}}\left(\cos^{-1}(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta)\right)d\omega \qquad \text{(eq.3)}$$

It was also noted that SWERA database provides mean daily values of radiation data. In order to consider the effect of hourly variation of incident solar radiation on the panels, monthly average of daily values were converted into hourly values using known correlations in literature. Hourly values of GHI was estimated using well known models Collares – Pereira and Rabl model and hourly diffuse values were computed using Liu and Jordan model [3].

2.3 PV & CPV performance

In order to estimate the performance advantage of PV and CPV technology at a particular location, the output energy per square meter of area from both the systems are calculated and compared. CPV technology uses the direct radiation and needs to be continuously tracked whereas PV systems can have fixed tilt or single axis tracking. It is a common practice to mount fixed tilt angle panels at latitude angle. For panels mounted in Bangalore, it is seen that east west single axis tracking provides higher benefits compared to fixed tilt angle[11]. Incident radiation on single axis tracked panels was calculated using the HDKR model for anisotropic sky. More details about this calculation procedure can be found elsewhere [11].

The performance of PV panels depends not only on the incident radiation but also on local weather conditions such as ambient temperature and wind velocity. It is known that increased module temperature causes drop in output voltage and current leading to reduced output at elevated temperatures. Module manufacturers always provide temperature coefficient data for their modules to account for this performance drop. The temperature coefficients of power output for multicrystalline modules vary from -0.4%/K to -0.6%/K for every 1^0 change in temperature from STC conditions (25^0C). In this paper, a power temperature coefficient of -0.5%/K is taken for the analysis. There are correlations for calculating module temperature from ambient parameters. Due to the forced convective cooling effect provided by wind velocity, a correlation for module temperature that incorporates ambient temperature, irradiance and wind velocity effect would have a realistic estimate of module temperature. Due to lack of such correlations for Indian conditions, correlation proposed by TamizhMani et al [13] as shown below has been used in the analysis.

$$T_{\text{mod}}(^0C) = 0.943 \times T_{amb}\left(^0C\right) + 0.028 \times Irradaince - 1.528 \times windspeed + 4.3 \qquad \text{(eq.4)}$$

Here irradiance is in W/m^2; wind speed is in m/s. Wind velocity and ambient temperature data were taken from SWERA database. Lack of enough operational data for CPV modules forbids one from incorporating any temperature effect on performance of these modules.

System level solar to electric conversion efficiency of 23% for CPV and 13% for PV [1] have been used for evaluating output energy generation from these modules of one square meter size.

3. RESULTS AND DISCUSSIONS

The latitude wise variation of GHI and DNI values for 106 locations in India is shown in Fig. 2. It is seen that annual values of GHI range from 1700 – 2000 kWh/m^2 and DNI varies from 1200 to 2500 kWh/m^2. Northern regions of India show more DNI than southern regions. Variation of DNI and Diffuse radiation data for India with GHI is shown in Fig. 3. The DNI values show an increasing trend with the GHI values whereas the diffuse values are nearly constant for all the regions of GHI. It can be seen that there are places in India where the DNI values are higher than the GHI.

Ratio of radiation quantities is of interest due to the direct dependence of CPV on DNI. If the DNI ratio (i.e. DNI/GHI) is greater than one, it could be a potential region for installation of CPV. This also indicates if the contribution of diffuse radiation to GHI is higher (i.e. higher diffuse ratio), more benefit can be obtained by installing PV systems than CPV systems. Figure 4 shows the relation between the DNI ratio and diffuse ratio for locations in India. The plot shows an exponential behavior and it can be seen that the DNI ratio becomes more than 1 if the diffuse ratio is less than 0.45. It can be also noted that there are many locations in India (more than 75% of chosen locations) that have DNI ratio of less than one indicating CPV may not be the automatic choice for these regions.

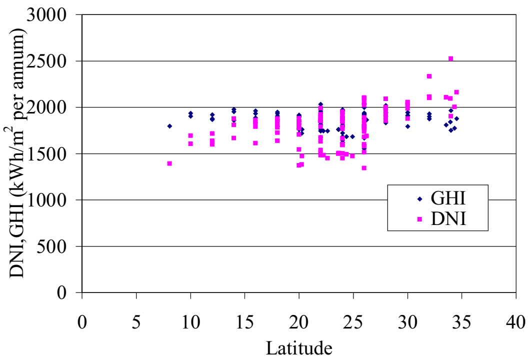

Fig.2 : GHI, DNI distribution in India

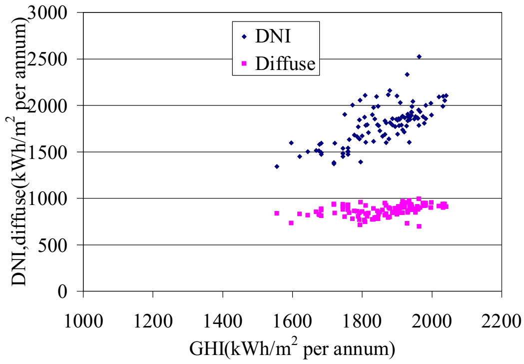

Fig. 3: DNI, Diffuse radiation variation with GHI in India

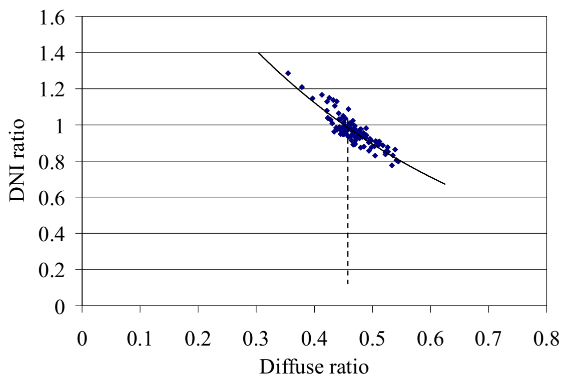

Fig. 4: Variation of DNI and diffuse ratio for locations in India

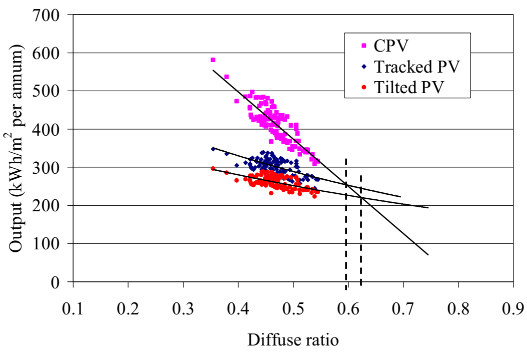

Fig. 5: Output variation with Diffuse ratio

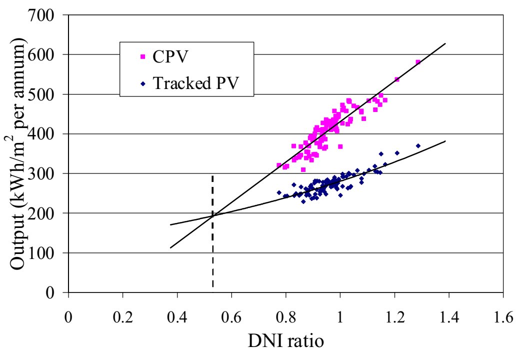

Fig. 6: Output variation with DNI ratio

Electrical output from PV and CPV systems are plotted in figures 5, 6 with chosen efficiency values. Figure 5 compares the output of CPV with a fixed tilt angle PV and an east-west tracked PV system. It may be recalled that fixed tilt angle values were chosen to be equivalent to the latitude angle. As expected, single axis tracked PV systems show higher output than fixed tilt angle systems that can be as high as 25% for some locations.

Though Fig. 4 indicates that there are only 25% of regions that have higher DNI (i.e. DNI ratio greater than one), it can be seen from Fig. 5 that CPV systems always produced higher output across all diffuse ratio regions. This is attributed to their superior conversion efficiency values. Figure 5 also shows linear dependence of CPV output with diffuse radiation ratio and nearly exponential dependence for PV systems. Extrapolating these trend lines leads to identification of regions in India that can provide output for a PV system that is equivalent to a CPV system irrespective of its superior efficiency values. For the chosen efficiency values of PV and CPV, it can be seen that tracked PV can provide output of a CPV if the diffuse ratio is more than 0.6. This "cut off" value of diffuse ratio can be used as a quick check to evaluate any region in India for their potential for CPV. However it can be also noted from figure 5 that there was no location among the chosen grid points in India that represented this case. Hence it is safe to mention that all regions in India can be beneficial to CPV, provided they have 75% higher conversion efficiencies than their PV counterparts. Fig. 6 shows the same result in terms of DNI ratio. This shows the cut-off value of DNI ratio for tracked PV to be competitive with CPV is 0.55. Figure 7 shows the negative effect of module temperature on tracked PV. This shifts the cutoff diffuse ratio to 0.64 instead of 0.6. Temperature effects also cause more scatter in the relation between output and diffuse ratio.

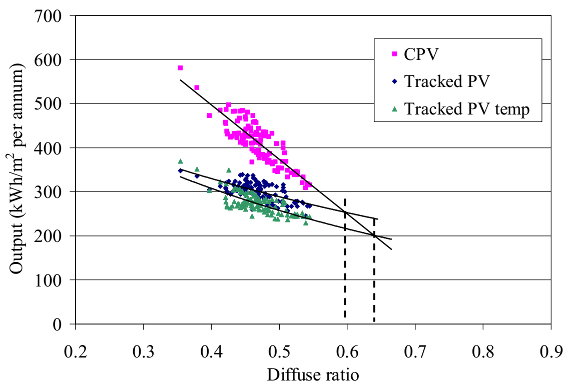

Fig. 7: Effect of temperature on PV output

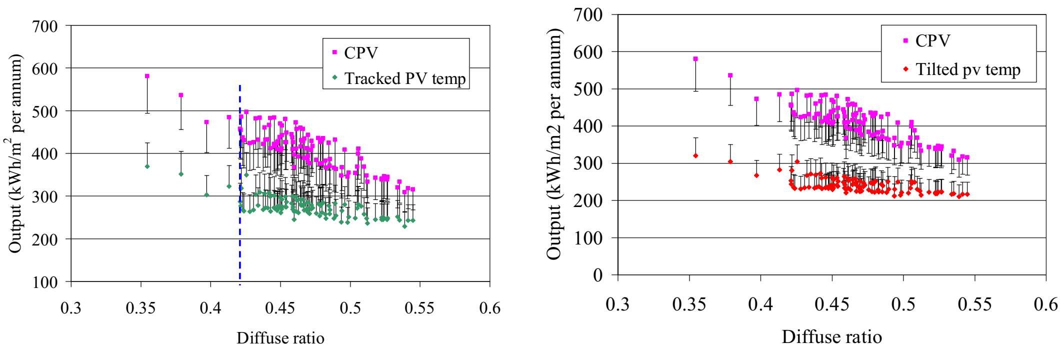

Fig. 8: Sensitivity of output values on cut off diffuse ratio

As the input solar radiation data is estimated based on satellite data and models, there are chances that it may vary from the actual radiation available at a location. Due to non availability of uncertainty in radiation values for a given location, it was decided to do a quick sensitivity analysis in terms of output. Assuming an uncertainty of 15% in the output due to variations in the solar radiation data, a worst case scenario for CPV (i.e. CPV having 15% lesser output and PV having 15% more output) has been plotted in Fig. 8. Error bars of 15% for PV (♦) and CPV (■) are added. For a single axis tracked PV (left side plot of Fig.8), it can be seen that the cut off value of diffuse radiation ratio is about 0.43 instead of 0.6. In this case, there are less than 5% of points that still show greater benefit for CPV. A quick check of these low diffuse ratio regions indicate that, not surprisingly, these 5% of regions are located in the north western part of India. These results can also be interpreted as the effect of variation in system efficiencies. For example, a recent analysis by Virar et al. (2010) on effect of soiling on CPV systems in field indicates that CPV systems show 14% drop in performance compared to 4% for flat plate PV systems. Such situations can cause output from CPV to be comparable to that of tracked PV in many locations in India.

On the other hand, ongoing research efforts to improve multijunction cell efficiencies can result in widening of the gap between CPV and PV making CPV suitable for all locations in India. It can be also noted that the sensitivity analysis carried out for a fixed tilt angle PV (right side plot of Fig 8) shows that there are about 37% locations (among the chosen 106 locations) in India that still show higher output from CPV despite 15% drop in efficiencies.

4. CONCLUSIONS

In this paper an analysis of suitability of CPV for India has been carried out using the data obtained from satellite based databases. 106 locations in India have been chosen to study the benefit of CPV with a single axis tracked PV system and latitude tilted fixed PV system. Analysis of solar radiation data for these locations showed an exponential behavior between DNI ratio and diffuse radiation ratio. Based on the chosen system level conversion efficiency values, CPV systems provided higher output for all regions in India compared to a tracked PV system and a fixed angle tilted PV system. Cut off diffuse radiation ratio was found to be 0.6 and DNI ratio was found to be 0.55. This could be used a first cut criteria for deciding a region for its suitability for installing a CPV system. However, there was no location in India among the chosen 106 points that met this criteria. Due to the uncertainty in radiation data values, output variations could be as high as 15%. A decrease of 15% output in CPV and an increase of 15% output from tracked PV shifts the cutoff diffuse ratio to 0.43 bringing many locations in the analysis that show no additional benefit due to CPV. Compared to a fixed tilt angle PV system, CPV systems provided higher output at about 37% of chosen locations even under worst case conditions.

NOMENCLATURE

Symbol	Name	Unit	Comment
φ	Latitude	°	Angular location north (+) or south (-) of the equator
λ	Longitude	°	Angular location east (+) or west (-) of the Greenwich meridian
δ	Declination	°	Angular position of the sun at solar noon with respect to the equatorial plane
ω	Hour angle	°	Angular displacement of the sun, east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, morning (-), evening (+)
θ_z	Zenith angle	°	Angle between the vertical and the line to the sun
G	Irradiance	W/m^2	Instantaneous values of irradiation
H	irradiation	kWh/m^2	Irradiation values normally expressed as daily or annual average
Subscripts			
B	Beam		
D	Diffuse		
N	Normal		
ss,sr	Sun rise, sun set		

The absence of subscript b or d means global (total) radiation.

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