Power & Energy Optimization in Solar Photovoltaic and Concentrated Solar Power Systems

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*Abstract***— Solar Energy purvey a pure Environment-friendly, ample and everlasting energy resource to humanity. Electricity can be generated using solar energy by two different technologies namely photovoltaic (PV) and concentrated solar power (CSP) systems. By using thermal energy storage technologies, CSP systems can store energy to generate electric power on cloudy days or overnight as compared to PV systems which results in flexibility in power network. Most important issue in energy market is the competitive cost of energy. Energy price of PV plant is less as compared to CSP plants. Whereas, CSP systems with thermal Energy storage capabilities can be effectively used to overcome intermittency issues of PV systems to balance demand with the supply of Electric power within safe levels of reliability by optimizing the Energy produced. This paper try to figure out the possible ways to optimize power and energy produced by Solar Energy technologies to reduce Carbon footprint. In addition to that, Solar PV and CSP systems are compared at two locations of tropical country India and simulations has been done in System Advisor Model (SAM) and presented graphically.**

*Index Terms***—Photo Voltaic (PV) Systems, Concentrated Solar power (CSP) Systems, System Advisor Model (SAM).**

I. Introduction

Solar PV and CSP systems have become highly competitive solutions for commercial, industrial and residential applications as a clean source of power in both grid connected and standalone mode of operation [1]. Energy can be supplied in a sustainable way through solar technologies across the globe [2]. By 2040, Renewable energies will achieve 34% of energy generation worldwide [3]. Being a clean source of energy, solar systems can play a vital role in reduction of greenhouse gases and can reduce global warming effects considerably [4]. Solar energy has achieved highest growth rate across the globe in the last few years due to fair visibility, vast availability and safe use for large & utility scale users [5]. Energy security is the major advantage of adopting solar systems for electricity generation as it justifies all expenditure and efforts in distributed form [6].

Solar Energy technologies are widely used in telecommunication base towers [7], water pumps [8], Smart grids, Micro grids and distributed generation [9], Building management systems [10], Electric vehicle charging [11], Satellites & Marine applications etc.

Solar PV system directly convert solar radiation into electricity by using PV cells [12]. In the last few years, PV system cost has dropped fiercely and is continue to sink [13]. By using efficient Maximum Power Point Tracking methods [14], PV systems can harness maximum possible amount of energy and can be integrated with the smart grids by power electronics approach [15]. In Concentrated Solar Power (CSP) Systems, Solar energy first converted into heat and then finally to electricity by using mirror or lenses & tracking system which concentrate sunlight into a focal point to heat a liquid, solid or gas. Power Tower, Parabolic Trough, Dish Stirling, Solar Chimney and Concentrating Linear Fresnel Reflectors are the examples of CSP technologies [16]. Most of the applications use Parabolic Trough Collector System that may achieve at least 25% efficiency. As compared to PV systems, CSP systems have higher running & installation cost and higher sensitivity to humidity & dust [17]. Various factors such as efficiency, reliability, cost, power quality and grid integration etc. will decide the future trends of solar energy. In addition to this, stochastic nature of solar irradiance is also a major challenge to effectively utilize endless sun power, therefore effective power and energy management techniques are needed to efficiently utilize solar energy systems worldwide. China has the world's largest solar photovoltaic power plant with a capacity of 1500 MW [18], whereas the world's largest concentrated solar power plant is in morocco with a net turbine capacity of 146 MW [19].

This paper includes basics of solar geometry and equations for sun radiation availability at any location. Electrical power generation through solar PV modules and concentrating solar collectors is also described briefly. Schemes for site selection, installation, commissioning and for cost are optimized followed by case study comparing solar PV and CSP systems at two locations of India and simulated.

II. Solar Geometry

A. Solar Radiation outside the Earth Atmosphere

Eruptions on Sun's surface & rotation cause magnetic disturbance in the earth's atmosphere [20]. Solar radiation outside the earth atmosphere is mandatory for accurate estimation of irradiance considering earth's rotation on its own axis and revolution around the sun [21].

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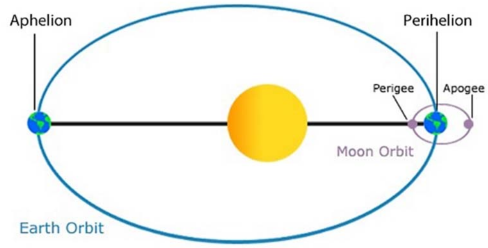

Fig. 1. Sun Synchronization through Seasons [22]

European space agency satellite mission is going to explore innermost regions of our solar system as shown below.

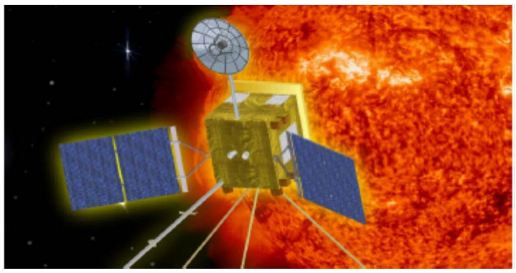

Fig. 2. Solar Orbiter around the Sun [23]

Changes in the intensity of solar radiation as well as the cosmic rays cause the temperature variation [24]. Outside the earth's atmosphere, energy flux collected from sun on a unit area is constant perpendicular to the sun rays. By Stefan – Boltzmann law, which is crucial for the weather study, relates black body radiation to temperature [25]. Solar radiation is equivalent to blackbody radiation of temperature 5779 Kelvin for a solar constant (Isc) of 1367 watt/ m^2 [26], whose value can be calculated on any day (n) of the year by the below equation.

$$Isc' = Isc\left(1 + 0.033\cos\frac{360n}{365}\right) \quad \text{Eq. (1)}$$

B. Solar Radiation inside the Earth Atmosphere

To predict the power generation from solar PV & CSP systems, solar radiation intensity prediction in clear sky is of great connotation [27]. Solar radiation scattering between the atmosphere of earth & surface play a vital role in the determination of geometrical & spectral distribution of sky radiance path [28]. Solar irradiance is not stationary and this process change depends upon the time and day of the year. Zenith angle (θz) can be used to forecast solar radiation, which is deterministic & can be calculated by earth's position around the sun [29] by using below equation.

$$\mathrm{Cos}\,\theta z = \mathrm{Sin}\,\Phi\,\mathrm{Sin}\,\delta + \mathrm{Cos}\,\Phi\,\mathrm{Cos}\,\delta\,\mathrm{Cos}\,\omega \quad \text{Eq. (2)}$$

Where δ is angle of declination, Φ is latitude and ω is the hour angle. Hour angle (ω) is zero at noon, positive and negative in morning & afternoon respectively and changes by a rate of 15^0 per hour. Declination angle and sunset hour angle can be determined using below equations.

$$\delta = 23.45 * \mathrm{Sin}\left\{\left(\frac{360}{365}\right)(284+n)\right\} \quad \text{Eq. (3)}$$

$$\omega = \cos^{-1}(-\tan\phi\tan\delta) \quad \text{Eq. (4)}$$

Below equation relates average of monthly global radiation (H) and sunshine hours (S) on daily basis based on the regression of first order.

$$\frac{H}{Ho} = a + b\,\frac{S}{So} \quad \text{Eq. (5)}$$

Where, So is the length of the day or maximum number of sunshine hours which can be calculated as given below.

$$So = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \quad \text{Eq. (6)}$$

In Solar CSP systems, direct normal irradiance directly impact generation of electricity calculated as below.

$$I = Ics * Kc \quad \text{Eq. (7)}$$

Where Ics and Kc are the clear sky direct normal irradiance & clearness index respectively. Beer- Lambert law is usually used to calculate clear sky direct normal irradiance in radiative transfer model as given below [30].

$$Ics = Io * e^{-m\tau} \quad \text{Eq. (8)}$$

Where m and τ are the relative optical air mass and depth of atmosphere respectively.

III. Electricity Generation Through PV And CSP Technology

A. PV System

In Solar PV Systems, Number of photovoltaic panels are used to make a module of required voltage and current, an equivalent circuit is shown below,

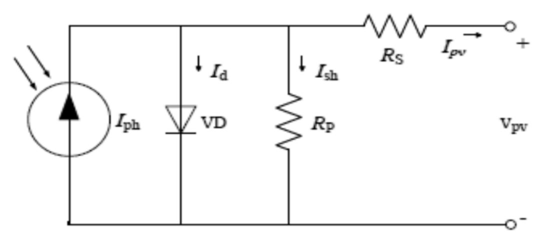

Fig. 3. Mathematical Model of Cells [31]

Solar cell $I-V$ characteristic equation is given below.

$$I_{pv} = N_{pp}\left\{ I_{ph} - I_d\left[\exp\frac{q\left(\frac{V_{pv}}{N_s N_{ss}} + \frac{I_{pv}R_s}{N_{pp}}\right)}{AKT} - 1\right] - \frac{\frac{V_{pv}}{N_s N_{ss}} + \frac{I_{pv}R_s}{N_{pp}}}{R_{sh}} \right\} \quad \text{Eq. (9)}$$

Where I_{ph} is the output photovoltaic current, I_d is the diode current, R_s is the series resistance, R_{sh} is the parallel resistance, I_{pv} is the output current & V_{pv} is the terminal voltage of PV module. By considering the temperature and light changes, PV cells output characteristic can be given as follows.

$$I_{ph} = \frac{S}{S_{ref}}\left[I_{ph,ref} + k_o(T - T_{ref})\right] \quad \text{Eq. (10)}$$

Performance ratio (P. R.) methodology can be used for power generation characteristic [32] as given below.

$$P.R. = \frac{\sum P_{pv}}{P_{nom}} * \frac{G_s}{G_{Ag}} = \frac{E_{pv}}{P_{nom}} * \frac{G_s}{H_{Ag}} \quad \text{Eq. (11)}$$

Where P_{pv} is measured AC power output (in kW), P_{nom} is nameplate nominal power (in kW), G_s is standard test condition sunlight in kW/m^2, G_{Ag} is global irradiance measured at the PV module in kW/m^2, E_{pv} is the AC energy output during the period of evaluation in kWh and H_{Ag} is the total global irradiance at the plane of PV module respectively.

B. CSP System

Various kind of reflective and refractive optical designs are used in CSP systems for concentration of direct normal irradiance [33] which include parabolic trough [34], concentrating linear Fresnel reflector [35], dish [36] and solar power tower [37]. A special kind of heat exchanger is used in CSP systems to absorb solar irradiance and converts it into heat and transfer that heat to water, air or oil flowing through as a fluid in collectors which can be tracking or stationary type [38]. At steady state, energy balance equation for absorber plate can be given as below [39].

$$q_u = A_p S - q_l \quad \text{Eq. (12)}$$

Where q_u is the heat transfer rate of air, oil or water used as working fluid, S is the solar irradiance absorbed by the absorber plate, A_p is the absorber plate area and q_l is the rate of heat loss by conduction & convection (from the bottom sides of absorber plate) and re-radiation (from the top of absorber plate). The instantaneous collection efficiency can be defined as the ratio of useful heat gain and incident radiation on the collector surface as given below.

$$\eta_i = \frac{q_u}{A_p I_T} \quad \text{Eq. (13)}$$

Where I_T is the incident energy on collector surface in one hour measured in kJ/m^2-h.

The performance can be measured by the below equation.

$$\eta_c = F_R\left[(\alpha\tau) - \frac{U_L}{I_c}(T_{WL} - T_a)\right] \quad \text{Eq. (14)}$$

Where η_c is thermal collector efficiency, F_R is heat removal factor of collector, $\alpha\tau$ is the transmissivity-absorptivity product of collector, U_L is coefficient of overall heat loss, I_c is the radiation incoming on collector surface, T_{WL} is the inlet fluid temperature and T_a is ambient temperature.

The power received on receiver from the sun in watts considering shading and blocking effects can be given as below.

$$Q_{received} = I_a \rho_m A_a \tau \alpha_r \; RS \quad \text{Eq. (15)}$$

Where I_a is the insolation in watt/m^2, ρ_m is the reflectance of mirrors, A_a is the aperture area, τ is the transmittance of glass pane, α_r is the receiver absorbance and R & S are the receiver intercept and shading factor respectively.

IV. Power And Energy Optimization Scheme

A. Optimal Site selection

Solar PV and CSP systems planner must consider supply and transmission capabilities in longer frame of time [40]. Location and Size of Solar power plants in large scale is a challenging task for system planners. Usually solar power plants are located in remote areas characterized by higher solar radiations, which can be very far from the load centers that account for very high transmission losses. Therefore, optimal location algorithm [41] is mandatory.

B. Optimal Installation and Commissioning

Performance ratio methodology can be used to compare PV and CSP systems across the globe at different locations [42]. Based on the geographical location and earth's declination angle, calculation of optimal tilt and tracking angle is mandatory to enhance power generation through PV and CSP system [43]. Net PV and CSP power generation can be enhanced by optimal use of existing distribution network and geographic information system [44].

C. Optimal cost of electricity

Levelized cost of electricity (LCOE) can be used as an analytical tool to compare different scales of investment & existing operation, which can be defined as the ratio of total life cycle cost and total lifetime energy production [45], which can be calculated by below formula.

$$LCOE = \frac{crf * C_{inv} + C_{O\&M} - C_{env}}{Q_{el,Net}} \quad \text{Eq. (16)}$$

Where C_{inv} is total investment cost, $C_{O\&M}$ is annual operating and maintenance cost, C_{env} is CO_2 rejected environmental cost, $Q_{el,Net}$ is net electric power production and crf is capital recovery factor as given below.

$$crf = \frac{k_d * (k_d + 1)^N}{\left[(k_d + 1)^N - 1\right]} \qquad \text{Eq. (17)}$$

Where annual discount rate (%) is k_d & N is depreciation time of the system in years [46]. Therefore, levelized cost of electricity should be calculated for different sites to optimize plant feasibility which is influenced by net power generation.

D. Miscellaneous

Solar PV and CSP power plants installation should meet consumer's economic and technical requirement by optimal selection of each photo energy installation component to get lowest cost of thermal & electrical energy generated in an operation [47]. N-Type monocrystalline silicon solar cell, which is the main component of PV system, offer highest conversation efficiency [48] among all types of solar cells. Concentrators with accurate line & point focus are the main component of CSP Systems [49], which are more sensitive to solar alignment errors than PV systems. Horizontal (tilt β) [50] and vertical axis (declination δ) [51] tracking can be used to increase the concentration of diffuse [52] (in case of PV) and direct [53] (in case of CSP) solar radiation. The performance of PV and CSP modules can be enhanced to their rated output by normalizing data to the same working conditions [54]. Short-circuit current, Open-circuit voltage and maximum power output of PV system, as given in Eq. (9), are affected by variation in temperature [55], which also affect the collector efficiency in CSP Systems [56], as given in Eq. (14). Air Mass, which describes the actual shape of solar spectrum depends on actual declination and altitude of sun [57] and considerably affect PV and CSP System Performance, which can be enhanced by adopting combined cooling and humidifying technology [58]. Both PV and CSP systems can be integrated with Smart Grids [59] during high demand season, which require an intelligent control system [60]. Wind velocity [61] and dust accumulation [62] also affect performance and leads to failure of PV and CSP systems [63]. Tilt angle (β) optimization is the best way to extract maximum solar energy from PV and CSP modules [64].

V. CASE STUDY

Solar PV and CSP systems are compared at two locations Panaji (15.49^{O} N, 73.8^{O} E) and Dehradun (30.31^{O} N, 78.03^{O} E) in India and Simulation has been done in System Advisor Model (SAM) [65] by National Renewable Energy Laboratory, USA.

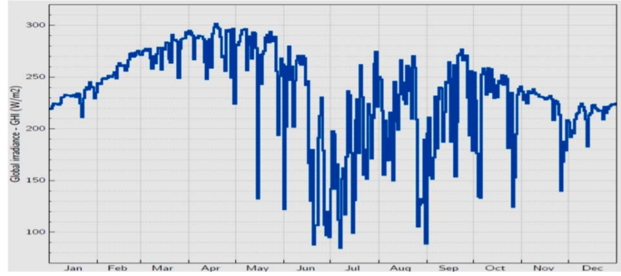

Fig. 4. Global Irradiance at Panaji

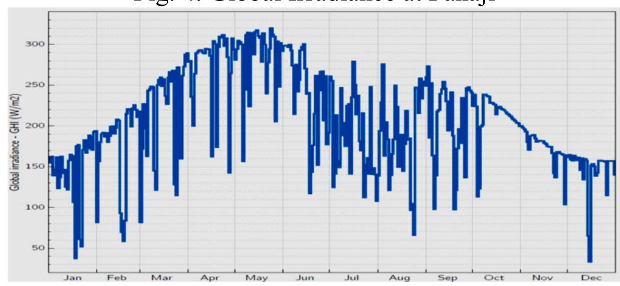

Fig. 5. Global Irradiance at Dehradun

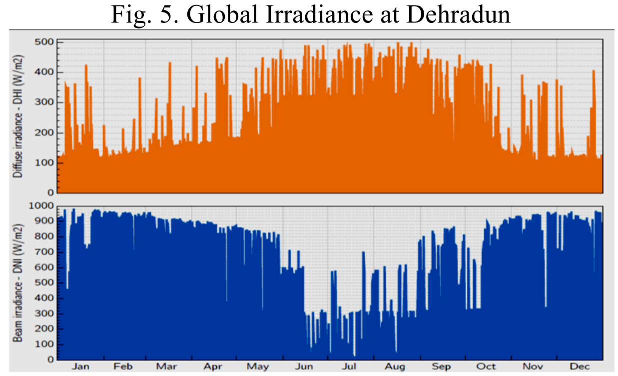

Fig. 6. Beam & Diffuse Radiation at Panaji

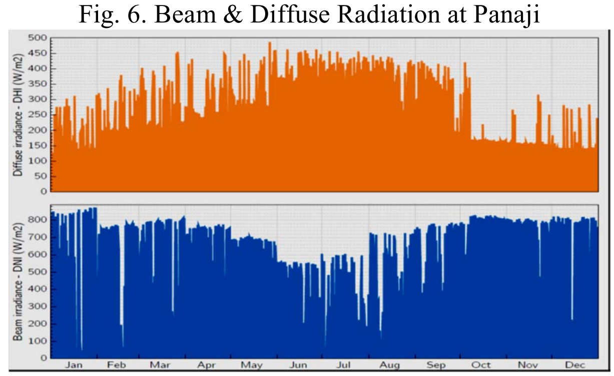

Fig. 7. Beam & Diffuse Radiation at Dehradun

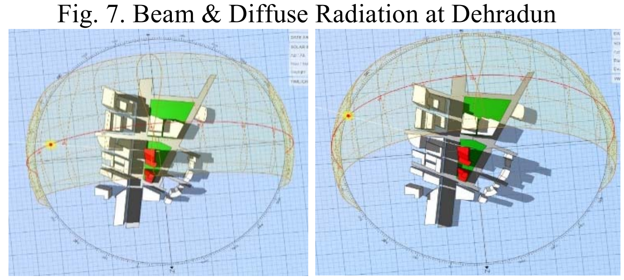
Fig. 8. Sun Path for Panaji & Dehradun

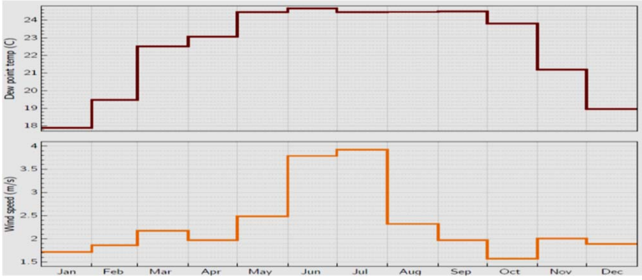

Fig. 9. Wind Speed & Dew point Temperature at Panaji

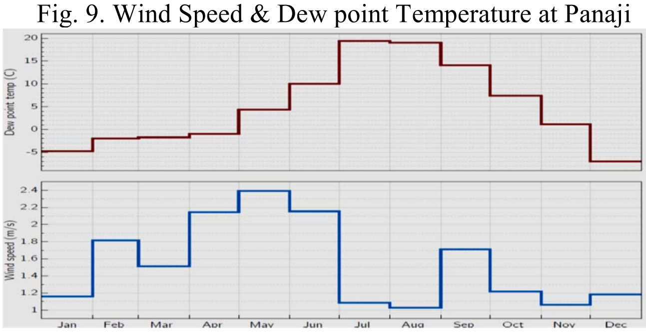

Fig. 10. Wind Speed & Dew point Temperature at Dehradun

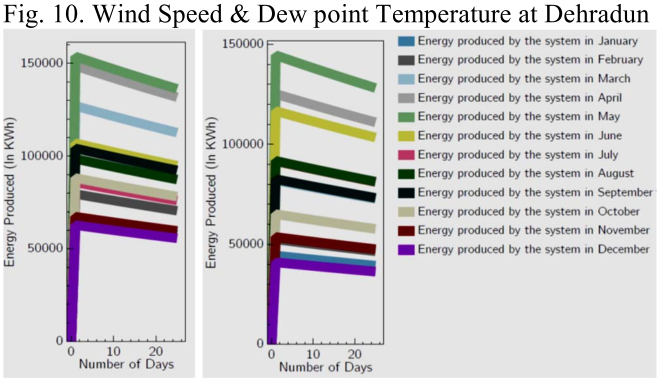

Fig.11. Energy Produced-PV System at Panaji & Dehradun

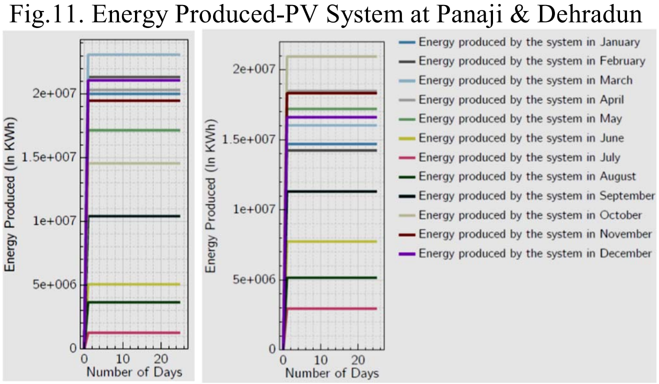

Fig. 12. Energy Produced-CSP System at Panaji & Dehradun

VI. RESULTS & CONCLUSION

Global Radiation is higher at Panaji as compared to Dehradun throughout the year which results in higher energy production by both PV and CSP system at Panaji. In the month of July, Average day length is lower at Panaji due to higher wind speed and lower beam radiation, which require optimum tracking to enhance energy production.

On 16th July	Panaji	Dehradun
δ	21.35^{O}	21.35^{O}
Φ	15.76^{O}	30.51^{O}
ω_s	96.33^{O}	103.31^{O}
S_o	12.8 hrs	13.7 hrs
Isc'	1323 W/m^2	1323 W/m^2
β OPTIMUM	0.76^{O} (summer) 30.76^{O} (winter)	15.51^{O} (summer) 46.02^{O} (winter)

Table. 1. Solar Geometry Calculations near Aphelion

Therefore, to extract maximum power and energy from Solar PV and CSP systems, site selection should be done based on climate and more specifically solar radiation. Performance ratio depends upon ambient conditions and vary with electrical design, climate & mounting conditions, which is very useful for short-term monthly, daily or instantaneous measurement of PV and CSP system output. Maximum power can be obtained by continuously adjusting the tilt angle at regular interval of time with the path of sun. By maintaining a very high capacity factor for PV and CSP systems, cost of energy can be minimized which is possible by using high efficiency tracking system and by reducing operational and maintenance cost.

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