Chapter 45
Tuning the Solar Power Generation Curve by Optimal Design of Solar Tree Orientations

Sumon Dey, Madan Kumar Lakshmanan and Bala Pesala

Abstract The paper presents a new design of a solar tree where solar panels are appropriately positioned like the leaves of a tree. Compared to fixed orientation solar panels, the main advantage of a solar tree is the ability to optimize the orientation of individual solar leaves in order to tune the power generation curves as required, for example, increasing the energy production during the winter months when solar insolation is low. Since orientation of solar panels is the key to achieve the maximum productivity of solar photovoltaic (PV) plants, data-driven and location-specific approach is employed to determine optimal orientation of five solar panels for solar tree structure for seven locations covering a large latitude range. Compared to the commonly employed latitude tilt orientation for solar PV modules, optimal solar tree design shows the feasibility of tuning the power generation curves to increase the power production in winter months or any other desired months. Scope for such tuning is higher for locations having high direct normal irradiance (DNI) and high standard deviation in the solar insolation curve. Also, higher number of solar panels in a solar tree provides higher degrees of freedom and hence larger flexibility to tune the power generation curve.

Keywords Solar tree · Tuning · Solar power curve

45.1 Introduction

The realization that renewable energy resources are essential to meet the energy demand of the future has led to a number of research works focusing on various areas of renewable energy. Major research in the field of solar energy focuses on

S. Dey · M. K. Lakshmanan · B. Pesala (✉)
Academy of Scientific and Innovative Research, Ghaziabad 201002, India
e-mail: balapesala@gmail.com

S. Dey
CSIR-Structural Engineering Research Centre, Chennai 600113, India

M. K. Lakshmanan · B. Pesala
CSIR-Central Electronics Engineering Research Institute, Chennai 600113, India

S. Singh and V. Ramadesigan (eds.), *Advances in Energy Research, Vol. 1*,
Springer Proceedings in Energy, https://doi.org/10.1007/978-981-15-2666-4_45

improving the efficiency of silicon solar cells [1], developing new solar cell materials such as perovskites [2], dye-sensitized solar cells [3, 4] and new technologies in the field of solar thermal energy [5]. Simultaneously, several studies are focused on the effective use of the existing solar panels by optimizing the tilt angle and by employing single/dual axis tracking methods. Solar panel installations require huge areas of shadow-free land. Increasing number of buildings in the urban areas puts a limit on the availability of shadow-free land for solar installations. Also, such installations in the rural areas and outskirts of cities leave less space for the farmers for agriculture. The land availability issue can be tackled if higher energy generation per unit area of land can be achieved. Moreover, there is a large deviation in the solar energy distribution pattern between various months due to varying solar insolation. As a general rule, installations in the northern hemisphere solar panels are placed facing south with a tilt angle equal to the latitude tilt and vice versa [6]. It can be seen from Fig. 45.1 that though Chennai (13.08° N) and Bangalore (12.96° N) have nearly same latitude, the insolation pattern for the two places varies significantly. This means that the latitude-based determination of optimal tilt angle for a location may not be correct always. The optimal tilt angle for a location also depends on various other geographical factors such as altitude of the location, clearness index of the sky and so on.

The latitude tilt configuration in the northern hemisphere always tends to increase the irradiance on panel in the months of October to February while reducing the irradiance in the months of April to August. This might not be desirable always. The energy demand curve over a year depends on the application. Some applications may demand high energy in the summer months while some other application may need uniform energy throughout the year.

The proposed work involves the development of solar tree structure in which the solar panels will be placed in optimized positions and orientations similar to the leaves of a tree. Data-driven location-specific calculations have been done to optimize the orientation of solar panels to tune the annual power generation curve. The objective of designing a solar tree is to decrease the land area requirement for obtaining equivalent amount of solar output. Further, aligning the solar panels at different orientations optimized for a geographical location based on actual radiation data provides flexibility to tune the power generation curve as per the need (e.g., to increase

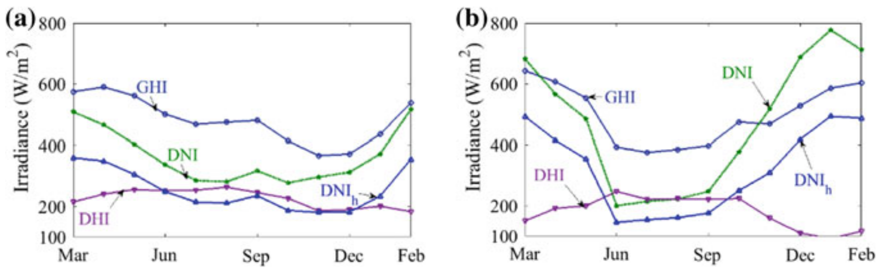

Fig. 45.1 Annual solar insolation pattern for **a** Chennai, **b** Bangalore

the power generation during the winter months) and takes care of the environmental factors that affect the insolation pattern of a location. In this paper, design of solar tree is demonstrated for seven locations. However, the design methodology is generic and can be easily extended to various geographic locations.

45.2 Design Methodology

45.2.1 Description of Solar Insolation Database

Meteonorm® software is used to obtain solar radiation database comprising of monthly, daily and hourly global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffused horizontal irradiance (DHI) for a typical year for any location. The Meteonorm solar radiation database is developed using weather satellite measurements incorporated into a site-time specific solar modeling approach. A typical year is obtained by averaging monthly solar radiation values over 20 years (1991–2010) [7]. DNI is the amount of solar radiation received per unit area by a surface perpendicular to Sun's rays. DHI is the amount of radiation received per unit area by a horizontal surface due to scattering of solar radiation by molecules and particles in the atmosphere. GHI is the addition of direct and diffused radiation on a horizontal surface as per the below equation.

$$\mathrm{GHI} = \mathrm{DHI} + \mathrm{DNI} \times \cos(\theta_z) \tag{45.1}$$

where θ_z is the zenith angle defined by the angle between the normal to observer surface and the line joining the Sun and the observer. Hourly global irradiance on horizontal surface is denoted as I. I_b refers to the hourly direct irradiance on a horizontal surface. Hourly diffuse irradiance on horizontal surface is denoted as I_d. 11 h (7 a.m.–5 p.m.) irradiance values for 365 days are used for further calculations.

45.2.2 Irradiation on a Tilted Surface

The amount of radiation received by a tilted surface is dependent on total solar radiation on the horizontal surface, position of the Sun and tilted surface orientation. The tilted surface orientation (ϕ) is described by its tilt angle β and surface azimuth angle γ. Tilt angle (β) is described by the angle between the horizontal surface and the plane of the surface. Surface azimuth angle (γ) is defined by the deviation of the projection of the normal to the surface on a horizontal plane from the north axis. The angular position of the Sun at solar noon is termed as declination angle (δ) which varies between $-23.45°$ and $23.45°$. The hour angle (HRA) is the angular displacement of the Sun east or west of the local meridian due to the rotation of the Earth on its axis at 15° per hour with morning negative and afternoon positive.

The solar position for a location, described by the solar zenith angle (θ_z) and the solar azimuth angle (γ_s), is obtained using the latitude of the location, declination angle and hour angle values. Solar zenith angle (θ_z) is the angle between the observer surface normal and the line joining the Sun and the observer. Complement of zenith angle is altitude angle which is given by the expression below:

$$\sin\alpha = \frac{\sin\delta\cos\varphi - \cos\delta\sin\varphi\cos \mathrm{HRA}}{\cos\alpha} \tag{45.2}$$

$$\theta_z = 90 - \alpha \tag{45.3}$$

Solar azimuth angle (γ_s) is the angle measured in clockwise from N to S axis from north to the projection of Sun on horizontal surface as shown in Fig. 45.2. It is given by the following equation:

$$\cos\gamma_s = \frac{\sin\delta\cos\varphi - \cos\delta\sin\varphi\cos \mathrm{HRA}}{\cos\alpha} \tag{45.4}$$

Incidence angle (θ) is the angle between the Sun's direction and normal to the tilted surface. Cosine of incidence angle is given by the following equation below:

$$\cos\theta = \cos\alpha\sin\beta\cos(\gamma - \gamma_s) + \sin\alpha\cos\beta \tag{45.5}$$

The global irradiance on a tilted surface I_ϕ consists of two basic components, namely direct beam component $I_{b,\phi}$ and the diffused component $I_{d,\phi}$, as shown in equation below:

$$I_\varphi = I_{b,\varphi} + I_{d,\varphi} \tag{45.6}$$

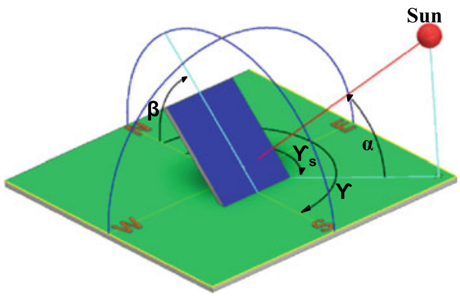

Fig. 45.2 Pictorial representation of Sun Earth Angles

where vector ϕ denotes the tilted surface orientation, i.e., surface tilt angle (β) and surface azimuth angle (γ). Figure 45.2 gives a pictorial representation of the Sun-Earth angles and the tilted surface orientation angles. The measured direct normal irradiance (DNI) is converted to direct beam irradiance on tilted surface by simple geometric relation given by the expression below:

$$I_{\mathrm{b},\varphi} = \mathrm{DNI}\cos\theta_{\mathrm{i}} \tag{45.7}$$

For the diffused irradiance component, an isotropic model given by Liu–Jordan [8] is used. The diffuse irradiance transposition factor is given by the equation below:

$$R_{\mathrm{d}} = \frac{1}{2}(1 + \cos\beta) \tag{45.8}$$

The diffuse irradiation on a tilted surface is given by equations below:

$$I_{\mathrm{b},\varphi} = I_{\mathrm{d}} \times R_{\mathrm{d}} \tag{45.9}$$

$$I_{\mathrm{d}} = I = \mathrm{DNI} \times \cos\theta_{\mathrm{z}} \tag{45.10}$$

The arrangement of solar panels similar to leaves of a tree enables tuning of the power generation curve as required. Power generation in certain months, especially months during which insolation is low, can be significantly improved through appropriate orientation of solar panels. The design of the solar tree is considered as an optimization problem which involves location-specific adjusting of the orientation of the solar panels to alter the solar power curve.

45.2.3 Optimization of Orientation of Panels

Tuning of the power generation curve is feasible if the solar panels are optimally orientated so as to extract maximum solar energy when desired. So, the energy captured by an inclined surface is defined in terms of surface azimuth angle (γ) and tilt angle (β). The objective of the optimization problem is to find the orientations of 'n' number of the solar panels so as to maximize the energy capture during the desired months. The value of tilt angle varies between (0°, 90°), and surface azimuth angle varies between (0°, 360°).

It is observed that significant amount of energy is lost in the months of March to September if solar panels are placed such that incident energy in the months of October to February is improved and vice versa. The optimization of the orientation of solar panels is done such that there is an increase in energy in the desired part of the year without losing much on the other part of the year. To achieve this, each solar panel of a solar tree consisting of 'n' number of solar panels is oriented in different directions. Incident energy in desired months (E_{i}) and annual average incident energy are calculated. The optimized configuration provides maximum increase in E_i while providing a maximum increase in annual average incident energy over horizontal. In other words, the objective of this process is to decrease the standard deviation of the energy curve.

45.3 Results and Discussion

The solar radiation profile for different locations is obtained from Meteonorm software. Conventional latitude tilt configuration results in increase incident energy on solar panels in the month of October to February for locations occurring in the northern hemisphere (NH), while locations situated in the southern hemisphere (SH) gain energy in the months of April to August when positioned in the latitude tilt configuration. However, the other half of the year that is April to August in case of NH and March to September in case of SH loses significant amount of incident energy. The irradiance profile for a number of locations was studied. Certain places have a widely fluctuating irradiation profile over the year. Locations with high difference between beam radiation on horizontal surface and direct normal irradiance were selected to show the tuning of the power generation curve. Solar tree configuration consisting of five numbers of solar panels is designed. Table 45.1 below shows energy gain obtained by the tree configuration and latitude tilt configuration over horizontal surface. As can be seen from the table, the tree configuration provides higher gain than latitude tilt in all cases. However, the gain is higher for latitudes ranging from 20° to 50°.

Figure 45.3 shows the energy curve obtained by tree configuration which demonstrates the tuning of the energy curve. The monthly maximum curve shows the maximum energy that can be extracted by means of tracking the Sun every month. Table 45.2 shows the energy gain obtained by the tree configuration for the different locations. Figure 45.3a shows the energy curve obtained by tree configuration

Table 45.1 Comparison of energy gain obtained by tree configuration over latitude tilt

Location	Latitude	Longitude	Energy gain with respect to horizontal orientation (%)		
			Monthly tracking	Latitude tilt	Solar tree configuration
Bangalore	12.96° N	77.58° E	7.74	3.19	3.26
Goa	15.48° N	73.81° E	7.39	3.60	3.62
Mexico	19.40° N	99.20° W	9.05	3.36	4.32
Austin	30.28° N	97.70° W	9.15	2.51	5.33
Beijing	39.93° N	116.28° E	13.91	7.55	9.27
Cape Town	34.00° S	18.60° E	13.79	7.38	8.51
Melbourne	37.82° S	144.97° E	13.26	4.96	8.43

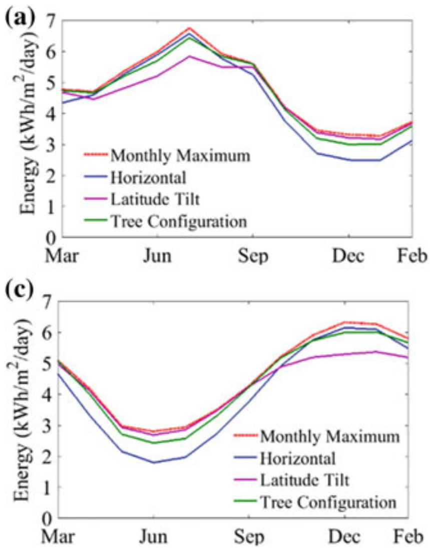

Fig. 45.3 Energy curve from solar tree configuration for **a** Austin, **b** Beijing, **c** Melbourne, **d** Mexico

Table 45.2 Energy gain with respect to horizontal obtained by the tree configuration for different locations

Parameters (in kWh/m^2/day)	Austin		Beijing	
	Value	% Improvement	Value	% Improvement
Annual average energy	4.59	5.33	3.95	9.27
Average energy in the desired months	3.37	16.12	3.24	30.74
Average energy in rest of the year	5.45	1.25	4.38	−1.40

for Austin. Tuning of the energy curve was done such that maximum energy is extracted in the months of October to February during which solar insolation is low in Austin. As seen in Table 45.2, energy gain obtained with respect to horizontal is as high as 16.12% without any loss of energy during the rest of the year. It is shown that with five panels tree configuration where each panel is oriented differently, an increase of 2.77% in incident energy with respect to latitude tilt is obtained. The standard deviation of the power generation curve is reduced by 16% with respect to horizontal.

Similarly for Beijing, from Fig. 45.3b, it can be seen that maximum energy extraction has occurred in the months of October to February using the latitude tilt configuration, while decreasing the energy in the rest of the year. With the tree configuration, 30.74% more energy is extracted in these months with an overall annual average increase by 9.27% with respect to horizontal. Though the gain obtained with tree configuration in October to February is slightly less than that of latitude tilt, 4.58% more energy is extracted in the other part of the year. The standard deviation of the

Table 45.3 Energy gain with respect to horizontal obtained by the tree configuration for different locations

Parameters (in $kWh/m^2/day$)	Melbourne		Mexico	
	Value	% Improvement	Value	% Improvement
Annual average energy	4.41	8.43	5.13	4.32
Average energy in the desired months	3.47	19.24	5.23	13.47
Average energy in rest of the year	5.73	0.69	5.11	−1.35

curve is reduced by 31.67% with respect to horizontal. For Melbourne, being located in the southern hemisphere, the latitude tilt has attempted to maximize the input energy in the months of April to August. But, it is clearly seen from Fig. 45.3c that significant amount of energy is lost in the months of October to February. Tree configuration designed to increase the incident energy in the months of April to August has resulted in an increase in 19.24% with respect to horizontal in these months. This has resulted in 10.26% increase in energy with respect to latitude tilt in the months of October to February. For Mexico, as can be seen from Fig. 45.3d, the annual energy curve is quite linear. Therefore, there is not much scope of improvement for the tree configuration. The energy curve obtained by tree configuration is equivalent to latitude tilt configuration (Table 45.3).

45.4 Conclusion

The analytical study presented in this paper has shown that there is scope for location-specific design of solar tree to alter the energy generation curve as desired. Although an attempt to increase the incident energy in the months of October to February decreases the energy in the months of March to September, a compromise can be achieved so as to obtain desired levelized irradiance throughout the year. Tree configuration consisting of five solar panels has been designed for seven locations based on the actual irradiance data. However, the design methodology is generic and can be extended to any geographic location. The feasibility to tune the power generation curves increases with the number of panels used as it gives higher flexibility. Future studies involve designing a solar tree with higher number of panels and multilevel solar tree for various locations.

Acknowledgements The authors would like to thank the Director General of CSIR, Director (CSIR-CEERI), Scientist-In-Charge (CSIR-CEERI) and Scientist-In-Charge (CSIR-CSIO) for their kind support and encouragement throughout the research work. Part of the research work has been carried out with equipment of CSIR Innovation Complex. We would also like extend our heartfelt gratitude to all our colleagues from the AcSIR Renewable Energy Program for all the support. Author Sumon Dey thanks Director, CSIR-SERC and CSIR-SRF fellowship for financial support.

References

1. V.V. Tyagi, N.A.A. Rahim, N.A. Rahim, J.A.L. Selvaraj, Progress in solar PV technology: research and achievement. Renew. Sustain. Energy Rev. **20**, 443–461 (2013)
2. G. Niu, X. Guo, L. Wang, Review of recent progress in chemical stability of perovskite solar cells. J. Mater. Chem. A **3**, 8970–8980 (2015)
3. H. Wang et al., Multifunctional TiO_2 nanowires-modified nanoparticles bilayer film for 3D dye-sensitized solar cells. Optoelectron. Adv. Mater. Rapid Commun. **4**, 1166–1169 (2010)
4. N.A. Ludin et al., Review on the development of natural dye photosensitizer for dye-sensitized solar cells. Renew. Sustain. Energy Rev. **31**, 386–396 (2014)
5. M. Liu et al., Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies. Renew. Sustain. Energy Rev. **53**, 1411–1432 (2016)
6. A. Mraoui, M. Khelif, B. Benyoucef, Optimum tilt angle of a photovoltaic system: case study of Algiers and Ghardaia. IREC 2014—5th Int. Renew. Energy Congr. (2014). https://doi.org/10.1109/irec.2014.6826904
7. Meteonorm: typical years. Available at: http://www.meteonorm.com/en/product/productpage/mn-produkt-dataset. Accessed 6 Feb 2017
8. B. Liu, R. Jordan, Daily insolation on surfaces tilted towards equator. ASHRAE J.; (United States) **10**, 526–541 (1961)