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Investigation of Shadowing Effect and Electricity Generation in Seasonally Adjusted Solar Photo Voltaic Arrays in Indian Sub-Continent

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Abstract: Solar photovoltaic panels are very widely used these days across the country. Their usage is also being encouraged by the central government and there are many subsidies in place as well. The tilt angle of the solar photovoltaic panel with the horizontal along with module orientation determines the transformation of energy into electricity. The optimum tilt angle for solar photovoltaic panels is considered for incident annual solar energy, this angle is usually kept unchanged for the year-round cycle. In this research work, we examine the optimum tilt angles of panels for the incident energy over panels on an annual and seasonal basis in combination with the shading effect of these panels over rooftops of Delhi (latitude 28.7° N), Nagpur (latitude 21.15° N) and Ahmedabad (latitude 23.02° N). Solar radiation data for the investigation purpose has been classified under 3 seasons, i.e., summer (May, June, July, August), winter (November, December, January, February) and equinoxes (March, April, September, October). It is observed that when panels are arranged facing down south and adjusted seasonally for optimum tilt angle; on an annual basis, they generate higher electrical energy and, in the summer, cast a larger shadow; in the winter, cast a smaller shadow as compared to panels which have fixed tilt throughout the year. This arrangement helps in reducing the solar heat flux via the roof in summer and increasing it in winter, thus, favourably affecting air conditioning load levelling in the structure.

Key words: Solar photo voltaic systems, solar radiation, tilt angles, irradiance, shadow length, heat flux, load levelling in buildings, latitude.

Introduction

Energy generation along with thermal comfort has become a characteristic parameter for a structure. The tilt angle of the solar photovoltaic panel with respect to horizontal along with module orientation determines the transformation of energy into electricity. Building integrated photovoltaic (BIPV) systems do not include the cost of site development, foundation, structural support, underground electrical distribution, etc. Indian government on a very wide scale is promulgating rooftop solar photovoltaic system utilisation, especially in urban areas. Hospitals, schools, and other community centres are being encouraged to make use of their existing infrastructure.

BIPV has grown in popularity because of its performance and durability in the last few decades, and demand has been steadily increasing, and it stands today as a major tool for energy generation. The gradual introduction of BIPV in urban and rural areas results from ongoing government efforts, with urban areas benefiting most from knowledge and accessibility. Solar photovoltaic (SPV) modules atop the roofs of buildings such as educational institutions, hospitals, and

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workplaces are becoming commonplace. This approach also helps to reduce greenhouse gas emissions, which contribute to climate change. BIPV is being studied across the world in order to better understand and increase its efficacy.

The importance of optimum tilt angles and azimuth angles for BIPV applications is highlighted through the case study on a building in Hong Kong on a yearly, seasonal, and monthly basis. Further underlying the importance of understanding the local weather conditions while studying BIPV applications (Yang et al., 2007). For Delhi city, it was determined that energy collected through flat plate solar collectors is significantly increased by varying the angle of tilt 4 times a year (Jamil Ahmad et al., 2009). The significance of the shadow on the mathematical model is assessed in the BIPV module from nearby adjacent structures. The model highlights the significance of negative shadow in improving the efficiency of the BIPV heating system (Yadav et al., 2018). The performance of various sun trackers was observed at differing latitudes across Europe and Africa. Perez's anisotropic model has been applied to analyse solar energy in numerous African and European locations and to calculate energy gains (Bahrami et al., 2016). For flat-plate collectors, the optimum tilt angle was investigated in Belgrade on a yearly, seasonal, and monthly basis, and the magnitude of solar energy on the area of rooftop PV panels was compared by adjusting the tilt angle on a yearly, annual, and monthly basis (Despotovic et al., 2015). Solar power in various Nigerian cities situated in strategic place is analysed to highlight the energy status and unreliable grid connections. A study was undertaken to analyse the effectiveness of using roof top SPV in different residential areas with hourly metrological data analysis in the traditional metrological manner of the year (Okoye et al., 2015). By recording monthly data on the horizontal surface, there is a clear monthly average indicator of global solar radiation, the optimum annual tilt angle is examined and analysed by modifying the energy gathered to make a partial change in the horizontal angle of inclination of a flat plate collector in 10 locations throughout the world (Ahmad et al., 2009). The optimal tilt angle and inclination of the solar collector for Brunei Darussalam were established with the help of a mathematical model to examine absolute solar radiation on a slanted surface. The determination was made on a daily basis as well as for a set amount of time (Yakup et al., 2001). The monthly mean of daily solar radiation for Tabriz was estimated using a combination of artificial neural network (ANN) models and several empirical methods (Mobtaker et al., 2016). Variations in incident solar energy and shadow length for panels fixed at seasonal optimum tilt angles were investigated as compared to annually fixed tilt angle for one city (Duggal et al., 2019). The effect of tilt angle on the performance of the grid-integrated solar PV plant using two types of tilt angle test plants, one fixed angle and two seasonal tilt angle at Bikaner and their performance over the year was compared (Sharma et al., 2022).

The variation in incident solar irradiance at optimum tilt angles for solar panels with fixed tilt are compared in this work. On a monthly and seasonal basis, the magnitude of energy incident on the panels, as well as the shading impact of these panels on the rooftops at Delhi (latitude 28.7° N), Nagpur (latitude 21.15° N), and Ahmedabad (latitude 23.02° N), are used to find the optimum tilt angles. For investigation, the data has been divided into 3 seasons, namely, summer (May, June, July, Aug), winter (November, December, January, February) and equinox (March, April, September, October). In this research, we looked at the absolute solar irradiance over a south-facing surface to optimise air conditioning underneath the structure, load levelling is being done.

Mathematical Formulations

The amount of radiation exposure in a slanted area can be indicated by

$$S_t = S_{bh} R_b + S_{dh} R_d + Sgh \rho R_r \quad (1)$$

where S_t is total radiation on the tilted surface, ρ is the ground reflectivity. $S_{dh,}$ S_{bh} and S_{gh} are diffused radiation, beam radiation and global radiation over horizontal surfaces respectively. R_b, R_r and R_d are the beams; surface reflected and diffuse radiation tilt factors (tilt factor is the ratio of sloping surface radiation to horizontal surface radiation, or the conversion factor used to multiply horizontal surface radiation to get sloping surface radiation), which is expressed as follows:

$$R_b = \text{Cos}\ \theta / \cos \theta_z \quad (2)$$

where θ is the incident angle of beam radiation on a tilted surface.

Solar Radiation on Tilted Solar Photo Voltaic (SPV) Panels

Global sun and radiation measurements are traditionally horizontal. Data on solar radiation on inclined surfaces is only occasionally available. Numerous researchers have examined solar radiation in sloping terrain. The researchers have used ANN models in conjunction with empirical models to predict solar radiation across cities worldwide for varying applications. The three total solar radiation components incident on a slanted surface are beam radiation, diffuse radiation, and ground-reflected radiation. The debatable perception that the sky is an isotropic/anisotropic source is considered in the diffuse radiation approximation. Some researchers relied on the simple concept of an isotropic radiation distribution, whereas others viewed the sky as an anisotropic source. We used an explicit evaluation of an isotropic model to determine hourly global radiation across inclined surfaces to find the appropriate collector tilt for various solar energy applications, along with a study of total global radiation at different slanted surfaces in the Indian region.

Computational Results and Discussion

Wattage and tilt relative to horizontal are two general characteristics of solar PV modules. This is the viewpoint that has been researched and analysed. The panel being considered has a power rating of 33

Table 1: Seasonal variation of solar radiation incident on panels

New Delhi					
Season of year	*Mean declination angle (°)*	*Total solar radiation on south facing surface*		*Increment in solar irradiance*	*Angle of incidence*
		Value of ß (in Wh/m²)			
		Seasonally adjusted	*Fixed tilt (@ 28.68 °)*		
Summer (May, June, July, August)	19.13	5859 (@9.57 °)	5500	359 (6.52%)	9.57
Winter (Nov, Dec, Jan, Feb)	-18.96	6331 (@47.66 °)	5976	355 (5.94%)	47.66
Equinox (March, April, Sept, Oct)	-0.1	6519.44 (@28.8 °)	6519.58	0	28.8
Nagpur					
Season of Year	*Mean declination Angle (in °)*	*Total solar radiation on south facing surface*		*Increment in solar irradiance*	*Angle of Incidence*
		Value of ß (in Wh/m²)			
		Seasonally adjusted	*Fixed tilt (@ 28.68 °)*		
Summer (May, June, July, August)	19.13	5404.538 (@7.89)	5167.93	236.608 (4.58%)	7.89
Winter (Nov, Dec, Jan, Feb)	-18.96	6695.035 (@40.06)	6258.7	436.335 (6.97%)	40.06
Equinox (March, April, Sept, Oct)	-0.1	6338.322 (@21.12)	6338.19	0.132 (0.002%)	21.12
Ahmedabad					
Season of Year	*Mean declination Angle (in °)*	*Total solar radiation on south facing surface*		*Increment in solar irradiance*	*Angle of Incidence*
		Value of ß (in Wh/m²)			
		Seasonally adjusted	*Fixed tilt (@ 23.02°)*		
Summer (May, June, July, August)	19.13	6001.50 (@3.94)	5660.585	340.915 (6.02%)	3.94
Winter (Nov, Dec, Jan, Feb)	-18.96	7073.87 (@42.03)	6592.75	481.12 (7.30%)	42.03
Equinox (March, April, Sept, Oct)	-0.1	6643.06 (@23.17)	6643.27	-0.21	23.17

Table 2: Monthly variation of solar radiation incident on panels

New Delhi				
Month of the year	*Declination angle*	*Total solar radiation on south facing surface value of ß*		*Variation*
		Fixed tilt (28.7°)	*optimum tilt*	
Jan	-20.92	5565.06	5937	6.68%
Feb	-12.95	6356.54	6520	2.57%
Mar	-2.42	6793.44	6795	0.02%
Apr	9.41	6711.22	6867	2.32%
May	18.79	6211.86	6647	7.01%
Jun	23.09	5505.6	6011	9.18%
Jul	21.18	5095	5503	8.01%
Aug	13.45	5184.52	5412	4.38%
Sep	2.22	6038.06	6061	0.38%
Oct	-9.6	6534.78	6638	1.58%
Nov	-18.91	6278.74	6720	7.03%
Dec	-23.05	5703.66	6240	9.40%
Nagpur				
Month of the year	*Declination angle*	*Total solar radiation on south facing surface value of ß*		*Variation*
		Fixed tilt (21.15°)	*optimum tilt*	
Jan	-20.92	6147.3	6680	8.66%
Feb	-12.95	6799.67	7030	3.39%
Mar	-2.42	7099.23	7100	0.01%
Apr	9.41	6884.32	7024	2.03%
May	18.79	6479.99	6911	6.65%
Jun	23.09	5536.05	5954	7.55%
Jul	21.18	4217.07	4415	4.69%
Aug	13.45	4438.6	4576	3.09%
Sep	2.22	5146.88	5175	0.55%
Oct	-9.6	6222.33	6310	1.41%
Nov	-18.91	6123.94	6574	7.35%
Dec	-23.05	5963.91	6615	10.91%
Ahmedabad				
Month of the year	*Declination angle (in °)*	*Total solar radiation on south facing surface value of ß*		*Variation*
		Fixed tilt (23.02°)	*optimum tilt*	
Jan	-20.92	6450.92	7045	9.20%
Feb	-12.95	6993.39	7234	3.44%
Mar	-2.42	7324.27	7331	0.09%
Apr	9.41	7097.18	7244	2.07%
May	18.79	6699.47	7164	6.94%
Jun	23.09	6018.88	6523	8.37%
Jul	21.18	4935.54	5240	6.17%
Aug	13.45	4988.45	5163	3.50%
Sep	2.22	5633.86	5662	0.50%
Oct	-9.6	6517.78	6626	1.66%
Nov	-18.91	6502.05	7005	7.73%
Dec	-23.05	6424.64	7178	11.73%

watts at STP (Standard Temperature & Pressure). The occurrence of solar radiation in the panel is equivalent to generating electricity. The pattern of shadow and the improvement of power generation in the PV series from time to time has been considered by several stations. Table 1 shows the seasonal fluctuation in solar energy impacting panels for cities in India located at various latitudes. It also indicates that, when compared to fixed tilt arrays, more solar radiation is incident in the summer and winter.

Table 2 compares the occurrence of incidental solar radiation over solar panels at a fixed and optimum tilt for all three cities on a monthly basis. In all three cities, the impact of adjusting the arrays on the shadow of modules on the roof top is also examined.

For each season, Table 3 displays the shadow length of modules for the PV array's mean solar tilt angle. For all three cities, the shadow length of modules with fixed tilt angles is shown in Table 4 during the course of the year.

As observed in Figure 1, the electricity generation is enhanced in both winter and summer seasons for all stations and remained constant at Equinox. The amount of incidental solar radiation over rooftop determines the amount of incoming solar heat flux in the structure's interior environment, thus the shadow length pattern is examined in order to determine the air conditioning load.

Depending upon the climatic situation, shadow length favours a reduction in heat flux and thus cooling. The effects investigated are of noon time and these noon time effects will increase at other times of day. Figure 2 represents the shadow length of the PV array of unit length at noon time for varying angles of incidence. It is a well-known phenomenon that in hot and humid climates shadow length increases in winter and summer, whereas in mixed climates like Delhi, it increases in summer and decreases in winter to favour cooling in summer and heating in winter respectively. Thus, we examined how shadow length varied throughout the year for a fixed tilt angle PV array and a seasonally adjusted PV array, which assisted us in determining proper array spacing. The shadowing pattern shows a rather variable configuration for some stations. Figure 3 and Table 5 represent that at a high latitude station like New Delhi, variation in shadow length is greater in summer than in winter which will help in modifying the solar heat flux, enhanced in winter and reduced in summer. At station with low latitudes, this pattern is rather variable, where variation is greater in winter than in summer, in that case, it can only be used for space conditioning.

Summary and Conclusion

It is noticed that the panels facing due south in the northern hemisphere and adjusted seasonally at their optimum tilt angles generate higher electrical energy; 6.52%, 4.58% and 6.02% at New Delhi (latitude), Nagpur and Ahmedabad, respectively, in summer. The panels also generate more electrical energy 5.94%, 5.50%, 6.97% and 7.30% at New Delhi, Nagpur and Ahmedabad, respectively, in winter and 5-7% increased

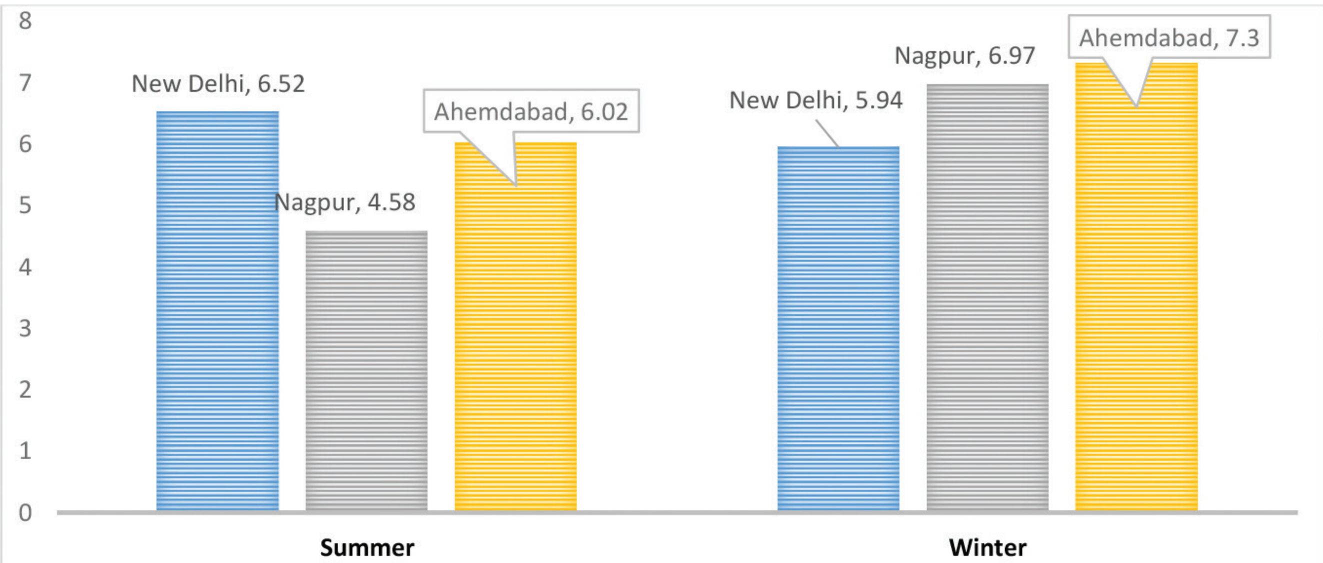

Figure 1: Improvement in solar irradiance (in %).

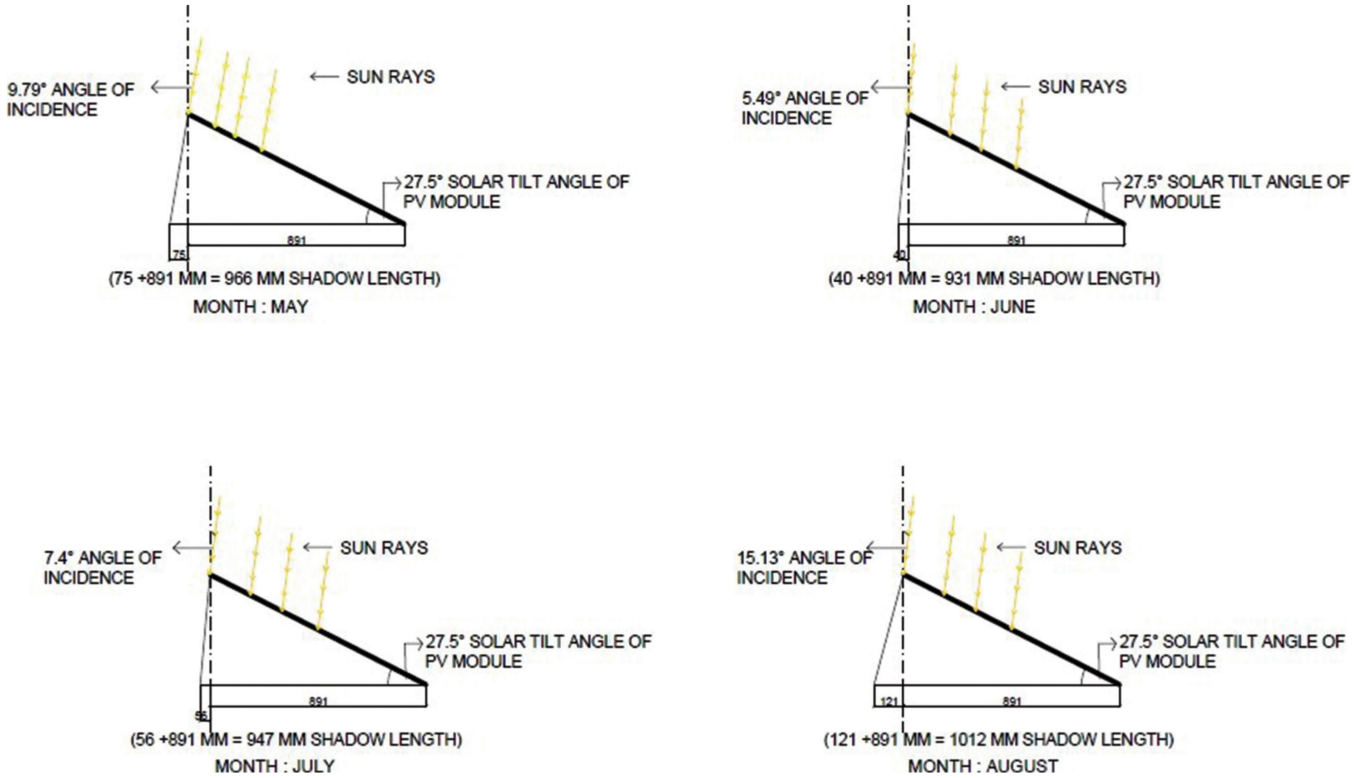

Figure 2: Shadow length of solar PV array at fixed solar tilt angle for summer.

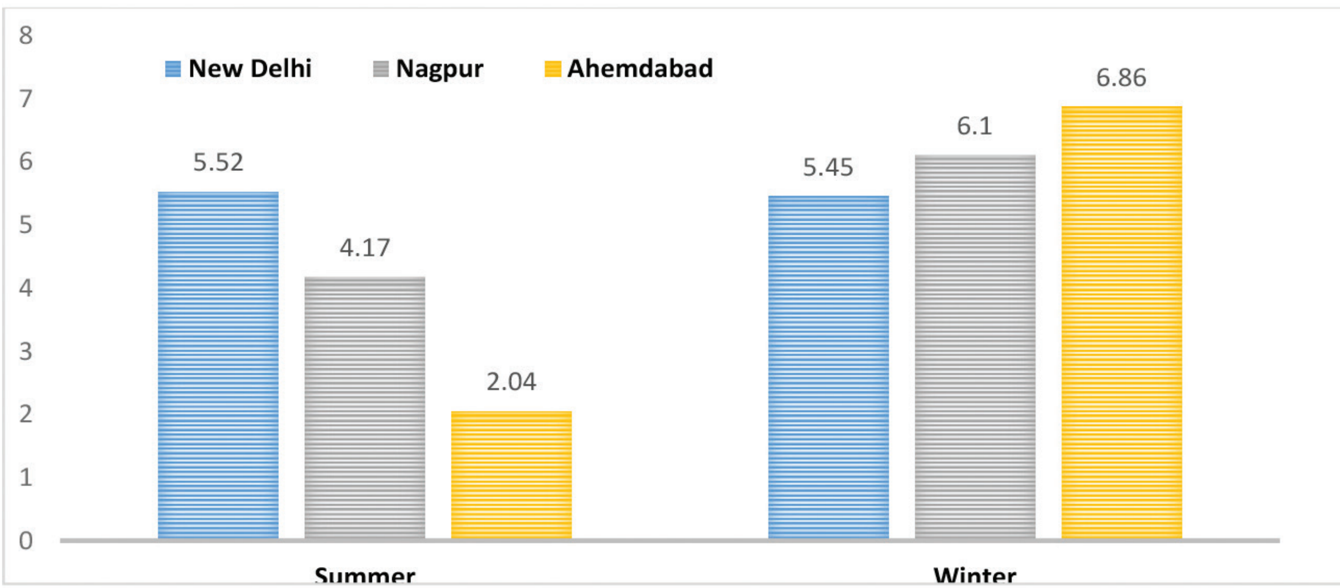

Figure 3: Variation in shadow length (in %).

electrical energy on an annual basis. The shadow effect of the panels on rooftop is such that in comparison to the panels at an annual fixed tilt angle, the shadow is bigger in the summer and smaller in the winter, this, in turn, lowers the inside solar heat flow in the summer and improves it in the winter, affecting the heating and cooling load inside favourably along with load leveling. So, in conclusion, noon time shadow length favours space conditioning in the buildings in all latitudes. Also to point out that shadow length is assessed for only a single array of 1 m length, for a bigger array, it will have a greater impact.

Table 3: Shadow length for mean solar tilt angle of PV array

Weather	Months	Mean solar tilt angle of PV array	Angle of incidence	Shadow length (m)
New Delhi				
Summer	May-August	3.75°	May = 9.79°	1.0093
			June = 5.49°	1.0043
			July = 7.4°	1.0065
			August = 15.13°	1.0157
Winter	Nov-Feb	50°	Nov = 47.49°	1.479
			Dec = 51.63°	1.61
			Jan = 49.50°	1.54
			Feb = 41.53°	1.321
Equinox	March-April, Sept-Oct	27.5°	March = 31°	1.164
			April = 19.17°	1.047
			Sept = 26.36°	1.15
			Oct = 38.18°	1.25
Nagpur				
Weather	*Months*	*Mean solar tilt angle of PV array*	*Angle of incidence*	*Shadow length (m)*
Summer	May-August	0°	May = 2.31°	1
			June = -1.99°	1
			July = -0.08°	1
			August = 7.65°	1
Winter	Nov-Feb	43.75°	Nov = 40.01°	1.3
			Dec = 44.15°	1.39
			Jan = 42.02°	1.34
			Feb = 34.05°	1.19
Equinox	March-April, Sept-Oct	27.5°	March = 23.52°	1.09
			April = 11.69°	1.01
			Sept = 18.88°	1.06
			Oct = 30.70°	1.14
Ahmedabad				
Weather	*Months*	*Mean solar tilt angle of PV array*	*Angle of incidence*	*Shadow length (m)*
Summer	May-August	1.25°	May = 4.28°	1.001
			June = -0.02°	1
			July = 1.89°	1
			August = 9.62°	1.003
Winter	Nov-Feb	46.25°	Nov = 41.98°	1.34
			Dec = 46.12°	1.44
			Jan = 43.99°	1.39
			Feb = 36.02°	1.22
Equinox	March-April, Sept-Oct	21.25°	March = 25.49°	1.105
			April = 13.66°	1.02
			Sept = 20.85°	1.07
			Oct = 32.67°	1.164

Table 4: Shadow length for fixed tilt angle of PV array

New Delhi				
Weather	*Months*	*Solar tilt angle of PV array*	*Angle of incidence*	*Shadow length (m)*
Summer	May-August	27.5°	May = 9.79°	0.966
			June = 5.49°	0.931
			July = 7.4°	0.947
			August = 15.13°	1.012
Winter	Nov-Feb		Nov = 47.49°	1.39
			Dec = 51.63°	1.469
			Jan = 49.50°	1.427
			Feb = 41.53°	1.407
Equinox	March-April, Sept-Oct		March = 31°	1.164
			April = 19.17°	1.047
			Sept = 26.36°	1.15
			Oct = 38.18°	1.25
Nagpur				
Weather	*Months*	*Solar tilt angle of PV array*	*Angle of incidence*	*Shadow length (m)*
Summer	May-August	20°	May = 2.31°	0.953
			June = -1.99°	0.951
			July = -0.08°	0.94
			August = 7.65°	0.986
Winter	Nov-Feb		Nov = 40.01°	1.227
			Dec = 44.15°	1.271
			Jan = 42.02°	1.248
			Feb = 34.05°	1.171
Equinox	March-April, Sept-Oct		March = 23.52°	1.09
			April = 11.69°	1.01
			Sept = 18.88°	1.06
			Oct = 30.70°	1.14
Ahmedabad				
Weather	*Months*	*Solar tilt angle of PV array*	*Angle of incidence*	*Shadow length (m)*
Summer	May-August	21.25°	May = 4.28°	0.959
			June = -0.02°	0.932
			July = 1.89°	0.944
			August = 9.62°	1.09
Winter	Nov-Feb		Nov = 41.98°	1.259
			Dec = 46.12°	1.309
			Jan = 43.99°	1.282
			Feb = 36.02°	1.195
Equinox	March-April, Sept-Oct		March = 25.49°	1.105
			April = 13.66°	1.02
			Sept = 20.85°	1.07
			Oct = 32.67°	1.164

Table 5: Comparative analysis of variation in shadow length

New Delhi				
Season of year	*Shadow length*		*Variation*	*Variation in %*
	At fixed tilt angle (28.68°)	*Seasonally adjusted*		
Summer (May, June, July, August)	0.958	1.014 (9.57°)	0.056 m	5.52
Winter (Nov, Dec, Jan, Feb)	1.404	1.485 (47.66°)	0.081 m	5.45
Equinox (March, April, Sept, Oct)	1.137	1.14 (28.8°)	0.003 m	0.26
Nagpur				
Season of year	*Shadow length*		*Variation (m)*	*Variation in %*
	At fixed tilt angle (28.68°)	*Seasonally adjusted*		
Summer (May, June, July, August)	0.96	1	0.04	4.17
Winter (Nov, Dec, Jan, Feb)	1.23	1.305	0.075	6.1
Equinox (March, April, Sept, Oct)	1.075	1.075	0	0
Ahmedabad				
Season of year	*Shadow length*		*Variation (m)*	*Variation in %*
	At fixed tilt angle (28.68°)	*Seasonally adjusted*		
Summer (May, june, July, August)	0.981	1.001	0.014	2.04
Winter (Nov, Dec, Jan, Feb)	1.261	1.3475	0.0865	6.86
Equinox (March, April, Sept, Oct)	1.09	1.09	0	0

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