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Global Solar Insolation Estimation and Investigation: A Case Study of Various Nations and Cities

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ABSTRACT Solar insolation is sun radiation converted to electrical energy and injected into the utility network using grid-connected solar power plants. Recently, in many nations' electricity grids, the share of power generated using solar photovoltaic (PV) power plants is rapidly increasing. In this case study, solar insolation levels on different latitudes with fix & two seasonal tilt angles have been measured using Meteonorm® software. For these latitudes, fourteen airport locations have been chosen across the globe. From the case study, it has been evident that a double seasonal tilt angle provides more global insolation as compared to fix tilt angle with a suitable azimuth angle. There is also a reduction in insolation level at fixed and two seasonal tilt angles if going away from the equator. Further, up to three seasonal tilt angles, there is sufficient enhancement has been observed in solar insolation. It is also analyzed that for multiple seasonal tilt angle based solar PV Plant, month-wise tilt angle selection is more important. Further Average, Rectangular, and Trapezoidal methods have been used for estimation of cumulative inclined insolation for a specific period and compared. From the comparison, the trapezoidal method has been found optimal for accurate estimation of cumulative inclined insolation.

INDEX TERMS Average Method, Error Comparison, Insolation Estimation, Rectangular method, Solar PV, PV module direction.

I. INTRODUCTION

Solar energy is renewable energy that is clean in nature and available in abundance. Solar insolation can be used to provide heat energy, light, and electrical power for domestic as well as industrial applications. Sun radiations can be converted into electrical energy using different types of solar cells. Due to the easy installation of all necessary equipment in a competitive market, photovoltaic power is the best and least expensive option today in remote and rural areas [1]. These are being used along with the conventional system in many developed and developing countries. Utilizing the PV energy efficiently and cost-effectively optical design of the PV systems with proper knowledge of the devices and system components is very important. Solar radiation at the surface of the earth undergoes short and long-term variations that are influenced by changes in atmospheric composition and cloud cover [2]. From May to July month, maximum insulations can vary according to different wavelength ranges of the solar light spectrum [3]. The cells were tested under actual operating conditions at the site where they were installed, showing different spectral responses in the red, green, and blue bands.

Grid-connected solar photovoltaic (PV) systems are increasingly attracting the attention of the industry and are mainly motivated by the potential to provide an alternative to conventional fossil fuel generation [4]. This helps in meeting the increasing energy demands and helps to limit the pollution of the environment caused by fossil emissions. In this case study, insolation estimation has been carried out for different locations with a selection of direction and tilt angle of solar PV modules across the world with the help of

Meteonorm® and PVsyst® software [5]. This case study is mainly divided into two sections. In the first section, 14 airport locations have been chosen for insolation estimation on different tilt and suitable azimuth angles. In another section, three methods have been used to find the optimal method for estimation of cumulative inclined insolation for a specific period. To investigate the optimal method, India, Bikaner desert location Pyranometer measured data have been used.

II. ESTIMATION OF GLOBAL SOLAR INSOLATION

A solar PV plant completely depends upon solar insolation falling perpendicular to the module. As the sun moves from east to west during the day, it is difficult for the module to face directly the sun rays for the whole of the day [6-9]. To achieve this, the tilt angle is decided at each location. Alternatively, we can move the module by tracking the sun and solar insolation depending on the day of the year, the hour of the day, the tilt angle of the PV array. To get maximum solar insolation, there are many possibilities of tilt angle and azimuth angle as shown in Fig. 1.

In Dual-axis tracking, we can track east to west (hours of the day) with north to south (day of the year according to sun movement from cancer to Capricorn or vice versa) direction. In single-axis tracking, it can track only in the east to the west direction [10]. Due to the very high installation and operation and maintenance cost of single and dual-axis tracking plant, in Rajasthan (India), mainly the Fix tilt angle and two or four tilt seasonal angles are preferred [11-13]. But due to the unavailability of skilled labor for change tilt angle in the desert area, mainly fix tilt angle or maximum of two seasonal (summer and winter) tilt angle for large MW capacity solar PV plant is preferred. So, to get maximum insolation and electricity generation, it is necessary to study insolation on different tilt angles and azimuth angle [14].

A. SELECTION OF PV MODULE DIRECTION (AZIMUTH ANGLE) TO GET MAXIMUM SOLAR INSOLATION

Fix tilt angle solar PV plants have low installation and maintenance costs as compared to seasonal solar PV plant costs (have the extra cost of seasonal tilt MMS (module mounting structure) and cost in change tilt angle procedure). So for fix tilt angle plant, one can predict the angle equal to the latitude of location and direction of PV module in South (if the location in the northern hemisphere) or in North (if site location in south hemisphere), by sun-earth geometry but it is difficult to predict the unit electricity generation in digit format. So for the prediction of solar insolation in kWh/m^2, PVsyst® software is used. PVSYST can provide solar Global insolation (Direct + Diffuse insolation) very easily according to the azimuth and tilt angle of a solar PV plant [15], [23-27], [35]. PVsyst® considers true south zero degrees and true North + 180 degrees. Towards the East, it's considered a positive angle, and the west direction is considered a negative angle. It is explained in Table 1.

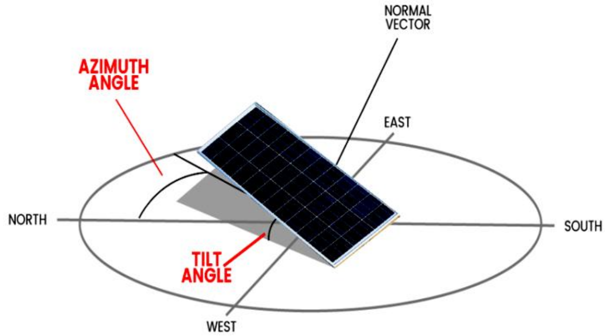

FIGURE 1. Different directions and tilt angle of the solar PV module.

TABLE 1. DIFFERENT DIRECTIONS AND TILT ANGLE OF THE SOLAR PV MODULE.

Compass Head	Azimuth Angle
North	180°
North-East	135°
East	90°
South-East	45°
True South	0°
South-West	-45°
West	-90°
North-West	-135°
North	-180

By considering a particular location (LAT, LONG), we can find out the cumulative inclined insolation for the Bikaner location (28°N, 73.1°E), Rajasthan (India). The below table represents the insolation values (kWh/m^2) on different azimuth and different tilt angles. In this table, the azimuth angles have been shown in the x-direction (left to Right) and tilt angles (Degree) has been shown in the y-direction (top to bottom). In practical consideration, due to the use of land, there is also a limitation on the tilt angle for obtaining the maximum insolation. Solar insolation in various directions and Tilt angles is provided in Table 2. In Table 2 of Global Inclined Insolation (kWh/m^2), the Azimuth angle vs Tilt angle of the module has been shown. In this table red colour represents the maximum value of insolation; yellow colour represents the mean value of insolation and green colour represents low-value insolation. For Bikaner location (28°N, 73.1°E), the following results can be concluded:

- There is a zero-degree tilt angle that has the same values 1903 kWh/m^2 in all azimuth angles because it represents Global horizontal insolation.

TABLE 2. SOLAR INSOLATION (KW/M^2) IN DIFFERENT DIRECTIONS AND TILT ANGLES

Tilt Angle Azimuth Angle	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°
-180°	1903	1840	1766	1682	1590	1489	1384	1285	1187	1099	1011	931
-150°	1903	1848	1783	1710	1630	1545	1455	1372	1285	1198	1115	1036
-135°	1903	1858	1804	1742	1676	1605	1532	1463	1388	1314	1243	1171
-120°	1903	1871	1831	1784	1734	1679	1622	1566	1507	1444	1383	1319
-90°	1903	1904	1895	1883	1863	1840	1809	1776	1735	1694	1641	1593
-60°	1903	1936	1958	1975	1981	1980	1969	1945	1918	1880	1838	1785
-45°	1903	1950	1985	2012	2028	2034	2031	2008	1984	1950	1905	1852
-30°	1903	1960	2006	2040	2064	2076	2077	2058	2035	2000	1956	1900
0°	1903	1969	2024	2066	2095	2112	2117	2099	2077	2043	1997	1938
30°	1903	1961	2007	2042	2067	2079	2080	2062	2039	2005	1960	1905
45°	1903	1951	1987	2014	2032	2038	2035	2014	1990	1956	1911	1859
60°	1903	1937	1961	1978	1985	1985	1975	1950	1924	1887	1845	1793
90°	1903	1905	1898	1887	1867	1885	1815	1783	1742	1702	1650	1601
120°	1903	1873	1833	1787	1738	1684	1628	1572	1513	1451	1390	1326
135°	1903	1859	1806	1745	1679	1609	1537	1467	1394	1319	1249	1178
150°	1903	1849	1784	1712	1632	1548	1459	1376	1289	1202	1120	1040
180°	1903	1840	1766	1682	1590	1489	1384	1285	1187	1099	1011	931

- To get maximum insolation, the best direction is south (zero-degree azimuth angle, shows in red colour).
- To get maximum insolation, we increase the tilt angle and get maximum solar insolation of 2117 kWh/m^2 on 30° nearly equal to the latitude. So it is the best angle for max insolation on 28 North latitude with south orientation.
- When we increase the tilt angle to more than 30°, there is a decrement in insolation values due to the sun path.
- When we shift the direction of the PV module towards the southeast or west, then there is a decrease in insolation values.
- If we put PV module orientation in the North direction, then we increase the tilt angle, then more lose indirect insolation.
- To get maximum insolation in the North Direction best suitable tilt angle is 0 °.
- In North Direction, we can get better Efficiency using the Thin Film Module (give a good generation in Diffuse Insolation).
- Poly and Mono Crystalline Si PV modules give better efficiency on direct insolation, so to get maximum electrical output select south orientation.

B. SELECTION OF TILT ANGLE OF SOLAR PV MODULE AT A PARTICULAR LOCATION

From the previous analysis, it is clear that the orientation for maximum insolation for fixed-tilt angle plants in the South. For seasonal tilt angles, we only change the tilt angle and freeze the azimuth angle in the south direction (in Northern Hemisphere) [36][39]. So there is a need to calculate the tilt angle for different seasons according to month [16-19]. To find a suitable seasonal tilt angle, Meteonorm® software has been used. Meteonorm® Software is a data source for engineering simulation programs in the passive, active, and photovoltaic applications of solar energy with comprehensive data interfaces. It is used for climatological calculations. Meteonorm® has 8350 weather stations all over the world.

Meteonorm® software containing climatological data for solar engineering applications at every location. It represents an average year of the selected climatological period based on the user's settings [20], [22-29]. The Meteonorm® insolation database is based on 20-year measurement periods, the other meteorological Parameters mainly from 1991-2010. Meteonorm® is a standardization tool that permits developers and users of engineering design programs access to a comprehensive, uniform meteorological data basis. This is a meteorological reference for environmental research, agriculture, forestry. This software can provide a database according to the user. It has the feasibility of edit Location (latitude, longitude), Tilt angle, Azimuth angle and it provides data in graphically and Table format. Step for using this software, are given below:

- Step-1: First Select the Location, azimuth angle, and Tilt angle.
- Step-2: Select data from Meteonorm® datasheets.
- Step-3: Select standard Meteonorm®.
- Step-4: After the selection of data, in the next strep automatic simulation start and finally give output in the graphically and Table format.

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TABLE 3. MONTHLY GLOBAL INCLINED INSOLATION (KWH/M^2) ON DIFFERENT TILT ANGLE WITH TRUE SOUTH.

Tilt Angle	Sep	Oct	Nov	Dec	Jan	feb	Mar	Apr	May	Jun	Jul	Aug	Total
1°	171	148	125	106	115	134	172	199	209	193	177	173	1922
3°	173	151	130	110	119	138	174	200	209	193	177	174	1949
5°	175	154	134	114	123	142	177	202	209	193	177	174	1974
8°	178	159	140	119	129	147	181	204	209	192	176	175	2008
10°	179	161	144	123	133	150	183	205	209	191	176	175	2028
13°	181	165	149	128	138	155	186	206	208	190	175	175	2055
15°	182	167	153	131	141	158	188	206	207	189	174	175	2070
18°	183	170	158	136	146	162	190	206	205	186	172	174	2089
20°	184	172	161	139	149	165	192	206	204	185	171	173	2099
23°	185	174	165	143	153	168	193	206	202	182	168	172	2111
25°	185	176	168	145	156	170	194	205	200	180	167	171	2116
28°	185	178	171	149	159	173	195	204	197	177	164	169	2120
30°	185	178	173	151	162	175	195	203	194	174	162	168	2120
32°	184	179	175	153	164	176	195	202	192	172	160	166	2119
35°	183	180	178	156	166	178	195	199	188	168	156	163	2112
38°	182	181	180	158	169	179	195	197	184	164	152	161	2101
40°	181	181	181	159	170	180	194	195	181	160	150	158	2091
43°	179	180	183	161	172	181	193	191	176	156	146	155	2072
45°	177	180	184	162	173	181	192	189	173	152	143	153	2057
48°	174	179	185	163	174	181	190	184	167	147	138	149	2031
50°	172	178	185	164	174	181	188	182	163	143	135	146	2011
53°	169	177	185	164	174	180	185	177	157	137	130	141	1977
55°	167	175	185	164	174	179	183	173	153	133	126	138	1952
58°	163	173	184	164	174	178	180	168	147	127	121	134	1912
60°	160	171	183	164	174	177	177	164	142	123	117	130	1883

TABLE 4. SUMMARY OF GLOBAL INCLINED INSOLATION (KWH/M^2) IN DIFFERENT SEASONS WITH TRUE SOUTH.

S. N.	Number of Tilt angle	Tilt Angle	Tilt Angle Month	Insolation in Month at that tilt angle (kWh/m^2)	Yearly Radiation (kWh/m^2)	Insolation % increment after increase number of Tilt Angle
1	Fix Tilt angle	30°	All 12 month		2120	
2	Two seasonal Tilt					
(i)	A. Summer Tilt Angle	5°	(Apr, May, June, July, Aug, Sept)	1128	2162	2.0%
	B. Winter Tilt angle	30°	(Oct, Nov, Dec, Jan, Feb, march)	1034		
(ii)	A. Summer Tilt Angle	5°	(may, June, July, Aug)	752	2174	2.5%
	B. Winter Tilt angle	30°	(sept, Oct, Nov, Dec, Jan, Feb, march, April)	1422		
(iii)	A. Summer Tilt Angle	13°	(May, June, July, Aug)	748	2188	3.2%
	B. Winter Tilt angle	43°	(sept, Oct, Nov, Dec, Jan, Feb, March, April)	1440		
3	Three seasonal Tilt Angle	5°	(May, June, July, Aug)	753	2217	4.6%
		28°	(Mar, Apr, Sep)	584		
		45°	(Oct, Nov, Dec, Jan, Feb)	880		
4	Four seasonal Tilt angles	5°	(May, June, July, Aug)	753	2220	4.7%
		23°	(Sep, Apr)	391		
		38°	(Mar, Oct)	376		
		45°	(Nov, Dec, Jan, Feb)	700		

By selecting a particular location (28°N, 73.1°E) Bikaner, Rajasthan, India, and by changing the value of the tilt angle, we got the value of insolation of all 12 months (January to December). In Table 3 consider the tilt angles on x-direction (left to right) and the name of the month on the y-axis (top to bottom, September to December to January to August for simplicity of season summer and winter). In Table 3 consider the tilt angles on x-direction (left to right) and the name of the month on the y-axis (top to bottom, September to December to January to August for simplicity of season summer and winter). In Table 3 of Global Inclined Insolation (kWh/m^2) each month V/s Tilt angle of the module, for a pictorial representation according to their values.

In this table red color represents maximum value Insolation; Yellow color represents the mean value

Insolation and Green color represents Low-Value Insolation. For Bikaner location (28°N, 73.1°E), Final results are in Table 4 and explained one by one-

- For fix Tilt angle, we got maximum insolation on angle 30 ° is 2120 kWh/m^2.
- For 2 seasonal Tilt, there are three choices. First, by using tilt angles (5° and 30 °); it can increase insolation by 2 to 2.5 %. Secondly, by using tilt angles (13° and 43 °), it can increase insolation by 3.2 % and in the third choice, it follows the thumb rule for two seasonal tilt angles equal to (Latitude+15 °) & winter season and (latitude-15 °) for the summer season.
- By using 3 seasonal tilt angles (5°, 28°, and 45°), it can increase 4.6% insolation. It's a great increment in insolation.
- By using 4 seasonal tilt angles (5°, 23°, 38°, and 45°), it can increase 4.7% insolation. It’s also a good increment as compared to fix and two seasonal tilt angles, but as compared to 3 seasonal tilt angles there is only a 0.1% increment, so it’s not preferable.
- For multiple seasonal tilt angle Solar PV Plant, only selection of tilt angle is not important, along the tilt angle month selection is more important.

C. RELATIVE STUDY OF CUMULATIVE INCLINED INSOLATION ON DIFFERENT LATITUDES (GLOBAL AIRPORT LOCATIONS) USING METEONORM SOFTWARE

From the above discussion, it is clear that to get absorption of direct insolation at a fixed array the tilt angle should be equal to the latitude. Further for better absorption of direct insolation, it is recommended that an average tilt angle be adjusted to Latitude + 15˚ during winter and Latitude - 15˚ during summer. To study the insolation on different locations of the world according to their latitude from the North Pole to the South Pole along with the effect of two seasonal tilt angles, 14 places have been selected. These selected locations are airports in different countries. In short, all 14 locations are shown Table 5 with the country name, city name, latitude, and longitude. By using Meteonorm® software, according to their tilt angle, global insolation data are collected in a simple format. In the below-mentioned table, Table 6 to19 of all 14 locations shows the global insolation in kWh/m^2.In this first location Greenland (82° North), for a fixed tilt angle plant, the tilt angle is selected equal to the latitude. Further for two seasonal tilt angles are also shown in Table 6. The global insolation is also affected by the altitude of location, so altitude is also taken along with location coordinates [37] [40]. The maximum considerable tilt angle is 90 °. Beyond 90 °s, it’s not allowable due to practical considerations; the

TABLE 5. LOCATION DETAILS (CHOSEN AIRPORTS) ACROSS THE WORLD WITH TRUE SOUTH.

S.no.	Location Name		Latitude	Longitude
	Country	City		
1	North pole	Greenland	82.3872°N	35.7086°W
2	Russia	Moscow	55.7494°N	37.3523°E
3	Germany	Berlin	52.5069°N	13.1445°E
4	Canada	Ottawa	45.4145°N	75.7120°W
5	Italy	Rome	41.9102°N	12.3959°E
6	China	Beijing	40.0799°N	116.6031°E
7	USA	Washington	38.9071°N	77.0369°W
8	India	Ladakh	34.1662°N	77.4966°E
9	India	Rajasthan	28.0440°N	73.0807°E
10	India	Maharashtra	19.0896°N	72.8656°E
11	South America	Brazil	23.4306°S	46.4730°W
12	South Africa	Cape Town	33.9715°S	18.6021°E
13	Australia	Canberra	35.3052°S	149.1934°E
14	South pole	Antarctica	78.630°S	46.758°E

PV module cell, sun along with pitch (distance between back-to-back modules).

To fix the tilt angle 82°, reaching insolation is 1186 kWh/m^2. For two seasonal tilt angles, optimum tilt angles according to months are highlighted. For two seasonal tilt angles considered according to month-wise insolation as from Apr to Sep (67°) and from Oct to Mar (90°). The sum of month-wise Insolation (in Table 6, values highlighted) comes 1222 kWh/m^2.

Sept and LAT+15 used from Oct-March) (From Table 7 to 15) and for the last 4 locations Tilt angle (LAT-15 used from Oct-Mar and LAT+15 used from Apr-Sept) (From Table 16 to 19). From Fig. 2, it is clear that:

- By using two seasonal Tilt surfaces, it can get 3.75 % more insolation at any latitude as compared to fixed Tilt.
- Moving towards Earth Pole (On both sides the North Pole and the South Pole) from the Equator, there is a decrement in insolation at the Fixed Tilt surface.
- Above selected 14 places, maximum insolation reaches at earth surface on a fixed-tilt surface at Cape Town, South Africa. Cape Town gets 5% more insolation as compared to Rajasthan.
- Compared to Rajasthan (225 meter Altitude), India (9 hours’ sunshine Duration), and Ladakh (7.5 hours’ sunshine duration), both places receive nearly the same amount of Insolation. Ladakh has fewer sunshine hours and also has a foggy season in January and February month, but due to high altitude (3960 meters), it receives more insolation. Ladakh and Rajasthan latitude separate by 6° horizontal separate by 1000 kilometer and altitude difference 3735meter.

- Maharashtra, India is near to the sea but gets less insolation, Due to the rainy season (humidity) in July, August, and September Month.
- By using two seasonal tilt surfaces, one can get 3.91% more insolation in Rajasthan (India).
- In Ladakh, by using two seasonal tilt surfaces we get a maximum increment rate of 7.96% per year due to high altitude.
- Due to high altitude and cold weather, a PV plant gives better performance at the Ladakh location.

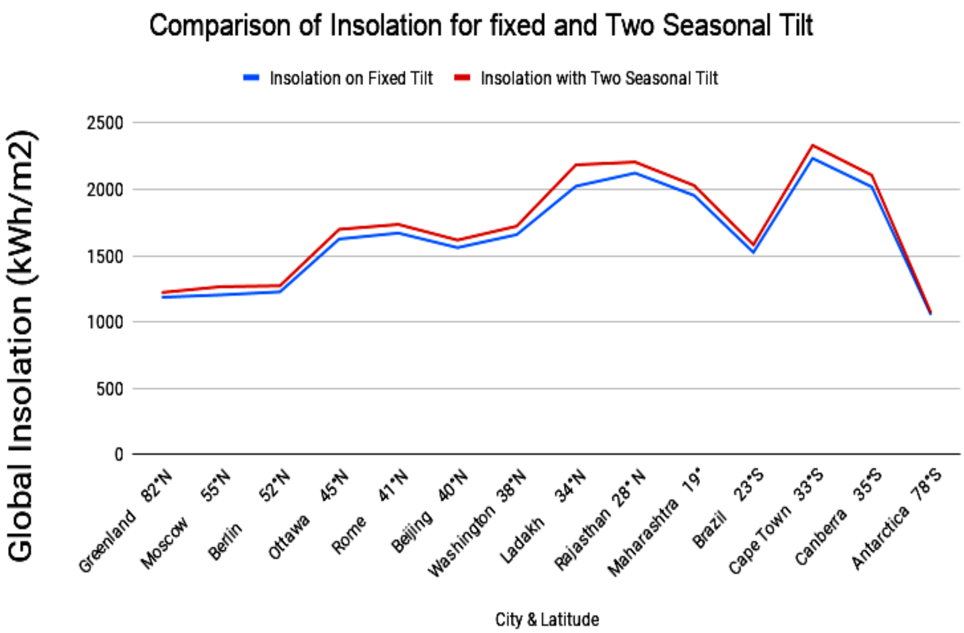

FIGURE 2. **Graphical representation of Insolation on fixed and two Seasonal tilt angles.**

TABLE 6. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT GREENLAND, NORTH POLE.

1
LOCATION NAME -Greenland, North pole
LATITUDE: 82.3872°N LONGITUDE: 35.7086°W ALTITUDE: 797m
Tilt ANGLE= LATITUDE-15 =67° for Apr-Sept
LATITUDE =82°
LATITUDE+15 =90° for Oct-March (Maximum allowable limit=90°)

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Rad.	Insolation with Two Seasonal Tilt Angle
67°	202	266	224	183	131	97	15	0	0	0	0	100	1218	1222
82°	200	257	212	173	126	98	16	0	0	0	0	104	1186	
90°	195	248	204	165	121	97	16	0	0	0	0	103	1149	

TABLE 7. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT MOSCOW OBLAST, RUSSIA.

2
LOCATION NAME - Sheremetyevo International Airport, Khimki, Moscow Oblast, Russia
LATITUDE :55.7494°N LONGITUDE:37.3523°E ALTITUDE: 150m
TILT ANGLE= LATITUDE-15 = 40° form Apr-Sept
LATITUDE = 55°
LATITUDE+15 = 70° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Rad.	Insolation with Two Seasonal Tilt Angle
40°	132	163	163	165	149	110	64	35	25	43	65	118	1230	1266
55°	127	150	148	151	141	111	66	39	28	49	71	123	1204	
70°	117	132	128	131	128	105	65	41	30	53	73	122	1124	

TABLE 8. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT GERMANY.

3
LOCATION NAME - Berlin Schönefeld Airport, Germany
LATITUDE :52.5069°N LONGITUDE: 13.1445°E ALTITUDE: 37m
TILT ANGLE= LATITUDE-15 = 37° form Apr-Sept
LATITUDE = 52°
LATITUDE+15 = 67° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Rad.	Insolation with Two Seasonal Tilt Angle
37°	149	161	162	159	154	122	81	40	29	34	58	103	1253	
52°	146	150	149	147	148	122	85	43	32	37	62	106	1227	1273
67°	136	132	128	128	133	116	84	44	34	39	62	103	1140	

TABLE 9. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT CANADA.

4
LOCATION NAME - Ottawa Macdonald–Cartier International Airport, Canada
LATITUDE: 45.4145°N LONGITUDE: 75.7120°W ALTITUDE: 53m
TILT ANGLE= LATITUDE-15 = 30° form Apr-Sept
LATITUDE = 45°
LATITUDE+15= 60° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
30°	153	172	174	188	170	144	108	69	74	91	116	153	1610	
45°	149	161	160	174	163	145	114	76	85	105	129	162	1625	1698
60°	138	143	138	151	149	138	114	79	93	114	135	162	1555	

TABLE 10. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT ITALY.

5
LOCATION NAME - Leonardo da Vinci–Fiumicino Airport, Rome, Italy
LATITUDE :41.9102°N LONGITUDE: 12.3959°E ALTITUDE: 52m
TILT ANGLE= LATITUDE-15 = 26° form Apr-Sept
LATITUDE = 41°
LATITUDE+15= 56° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
26°	153	186	192	210	192	151	119	81	65	80	97	144	1670	
41°	150	175	177	194	186	153	127	90	73	90	105	149	1670	1735
56°	139	154	154	170	169	146	128	95	77	95	108	147	1582	

TABLE 11. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT CHINA.

6
LOCATION NAME - Beijing Capital International Airport, Beijing, China
LATITUDE :40.0799°N LONGITUDE:116.6031° E ALTITUDE: 26m
TILT ANGLE= LATITUDE-15 = 25° form Apr-Sept
LATITUDE =40°
LATITUDE+15= 55° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insulation with Two Seasonal Tilt Angle
25°	157	172	152	142	140	131	116	92	87	101	113	144	1546	
40°	153	162	141	132	133	131	122	10 1	99	115	122	149	1560	1617
55°	143	144	124	117	121	124	121	10 5	105	122	125	145	1496	

TABLE 12 GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT USA.

7
LOCATION NAME -Washington Dulles International Airport, USA
LATITUDE: 38.9071°N LONGITUDE:77.0369°W ALTITUDE: 29m
TILT ANGLE= LATITUDE-15 = 23° form Apr-Sept
LATITUDE = 38°
LATITUDE+15= 53° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
23°	170	154	179	181	174	146	145	86	86	85	96	139	1642	
38°	166	145	165	168	168	148	156	96	100	96	105	143	1658	1722
53°	154	129	144	148	153	142	159	101	108	102	108	140	1587	

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TABLE 13 . GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT LADAKH, INDIA.

8
LOCATION NAME - Leh Kushok Bakula Rinpoche Airport, Leh, Ladakh, India
LATITUDE : 34.1662°N LONGITUDE:77.4966°E ALTITUDE: 3960m
TILT ANGLE= LATITUDE-15 = 19° form Apr-Sept
LATITUDE = 34°
LATITUDE+15= 49° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
19°	176	200	208	204	193	181	177	143	125	115	137	165	2023	
34°	176	200	208	204	193	181	177	143	125	115	137	165	2023	2184
49°	162	168	164	165	168	175	196	180	163	146	162	175	2023	

TABLE 14. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT RAJASTHAN, INDIA.

9
LOCATION NAME - Kodamdesar, Bikaner, Rajasthan, India
LATITUDE : 28.0440°N LONGITUDE: 73.0807°E ALTITUDE: 225m
TILT ANGLE= LATITUDE-15 = 13° form Apr-Sept
LATITUDE = 28°
LATITUDE+15= 43° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
13°	204	207	190	175	176	180	165	149	128	137	158	186	2056	
28°	202	196	177	165	171	183	177	171	150	159	176	195	2122	2205
43°	189	175	156	147	157	176	180	183	162	171	184	193	2074	

TABLE 15. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT MUMBAI, INDIA.

10
LOCATION NAME - Chhatrapati Shivaji International Airport, Mumbai, India
LATITUDE : 19.0896° N LONGITUDE: 72.8656° E ALTITUDE: 45m
TILT ANGLE= LATITUDE-15 = 4° form Apr-Sept
LATITUDE = 19°
LATITUDE+15= 34° form Oct-March

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
4°	199	200	145	118	121	143	162	146	138	150	157	196	1876	
19°	198	190	136	112	118	145	174	165	161	174	174	206	1953	2028
34°	185	170	121	101	109	139	177	176	175	188	181	205	1928	

TABLE 16. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT SOUTH AMERICA.

11
LOCATION NAME - Guarulhos International Airport, São Paulo, Brazil, South America
LATITUDE: 23.4306°S LONGITUDE:46.4730° W ALTITUDE: 743m
TILT ANGLE= LATITUDE-15 = 8° form Oct-March
LATITUDE =23°
LATITUDE+15=38° form Apr-Sept

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
8°	114	108	99	111	125	116	126	148	138	138	140	129	1491	
23°	121	120	114	127	137	119	123	141	129	129	136	130	1524	1582
38°	122	125	122	136	142	116	115	126	114	114	125	125	1483	

TABLE 17. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT SOUTH AFRICA.

12
LOCATION NAME - Cape Town International Airport, Cape Town, South Africa
LATITUDE : 33.9715°S LONGITUDE: 18.6021° E ALTITUDE: 45m
TILT ANGLE= LATITUDE-15 = 19° form Oct-March
LATITUDE = 34°
LATITUDE+15= 49° form Apr-Sept

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
19°	161	125	107	119	142	173	212	231	249	251	214	214	2198	
34°	175	143	125	138	157	182	210	216	226	232	208	221	2233	2331
49°	179	152	136	149	164	180	197	191	193	200	189	214	2145	

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TABLE 18. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT AUSTRALIA.

13
LOCATION NAME - Canberra Airport, Australia
LATITUDE : 35.3052°S LONGITUDE: 149.1934° E ALTITUDE: 570m
TILT ANGLE= LATITUDE-15 = 20° form Oct-March
LATITUDE = 35°
LATITUDE+15= 50° form Apr-Sept

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
20°	155	135	96	111	136	155	188	206	212	216	178	189	1976	
35°	168	156	111	129	152	162	186	194	194	200	172	194	2018	2106
50°	172	167	120	139	159	160	174	171	166	174	156	188	1946	

TABLE 19. GLOBAL INSOLATION (KW/M2) ON DIFFERENT TILT ANGLE AT ANTARCTICA, SOUTH POLE.

14
LOCATION NAME - Antarctica, South Pole
LATITUDE :78.630°S LONGITUDE:46.758°E ALTITUDE:3320m
TILT ANGLE= LATITUDE-15 = 63° form Oct-March
LATITUDE = 78°
LATITUDE+15= 90° form Apr-Sept (Maximum allowable limit=90°)

Tilt Angle	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Yearly Insolation	Insolation with Two Seasonal Tilt Angle
63	37	0	0	0	0	133	214	112	103	111	140	210	1060	
78°	40	0	0	0	0	139	214	107	97	105	137	215	1053	1068
90°	40	0	0	0	0	138	206	100	90	98	129	210	1012	

TABLE 20. COMPARISON OF SOLAR INSOLATION FOR A PARTICULAR LOCATION USING DIFFERENT SOFTWARE.

Solar Insolation on a particular location using different Software

Location - Bikaner, Rajasthan (27.9°N, 73 °E)

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY
PVSYST	158	181	189	204	209	193	177	172	174	177	170	149	2151
METENORM	162	180	195	203	209	194	177	173	175	178	173	152	2171
SOLAR GIS	169	177	216	207	209	185	170	178	184	208	172	167	2240

D. RELATIVE COMPARISON OF GLOBAL INSOLATION ON A PARTICULAR LOCATION BY USING THREE DIFFERENT SOFTWARE

For the calculation of global insolation, three software are used that are PVsyst®, Meteonorm®, and Solargis™. PVsyst® also fetches climatic data from Meteonorm® data but there is some difference in output data between all three software. For a particular location, Bikaner, Rajasthan, India (27.9 N, 73 E) monthly insolation (kWh/m^2) data were collected and analyzed in Table 20. To get this data, two seasonal tilt angles have been considered that are 5° (April to September), and 30 ° (October to March) in each software. From Table 20 following points can be noted,

- Maximum Global insolation is given by Solargis™ software.
- The difference between Meteonorm® and PVsyst® software is 20 kWh/m^2 yearly.
- The difference between Solargis™ and PVsyst® software is 88.3 kWh/m^2 yearly.
- The difference between Solargis™ and Meteonorm® software is 68.5 kWh/m^2 yearly.

Different-different solar companies use the software according to their ease. Maximum solar companies in Rajasthan, India followed PVsyst® software to give generation guarantees to clients after considering different types of system loss and it's also valid for government documents. To get more accuracy, always compare results from more software.

III. ANALYSIS OF INSTANT CUMULATIVE INCLINED INSOLATION USING DIFFERENT METHODS

To study the performance of solar PV plants on different angles, we must know the input insolation (W/m^2) on that tilt angle [38]. For a specific day or hour or minute period, cumulative insolation is found by using a Pyranometer that provides instantaneous insolation (W/m^2) data. For a specific solar PV plant cumulative inclined insolation, the tilt angle and azimuth angle of the PV plant and Pyranometer must be the same. Pyranometer provides instant insolation data in the form of Watt per meter square. By setting the period of the Pyranometer, we can get insolation in a period according to our demand (every 5 min or 10 min or 15 min). Cumulative inclined insolation is calculated by finding the area under the curve (between

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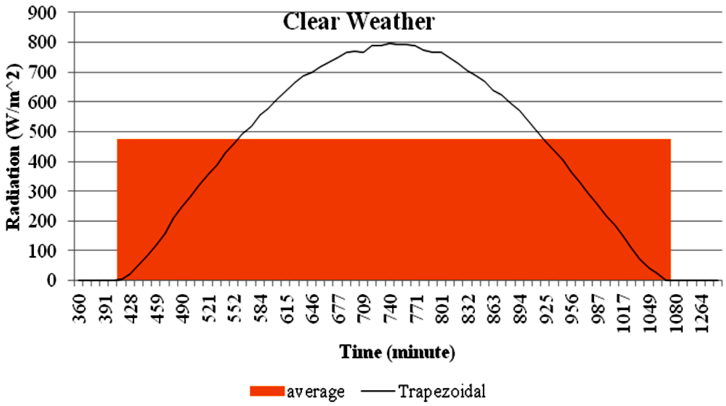

FIGURE 3. Graphical representation of cumulative insolation using the average method.

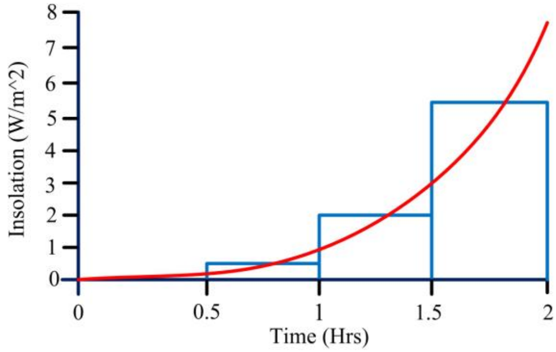

FIGURE 4. Application of rectangular method to calculate area under the curve.

TABLE 21: INCLINED INSOLATION DETAILS ON 17.10.2018 AT BIKANER, RAJASTHAN, INDIA

Entry Time	Inclined Insolation (W/m^2)	Entry Time	Inclined Insolation (W/m^2)	Entry Time	Inclined Insolation (W/m^2)
17-10-2018 06:00	0	17-10-2018 10:25	663	17-10-2018 14:43	599
17-10-2018 06:10	0	17-10-2018 10:36	686	17-10-2018 14:54	570
17-10-2018 06:21	0	17-10-2018 10:46	700	17-10-2018 15:04	538
17-10-2018 06:31	0	17-10-2018 10:56	719	17-10-2018 15:14	503
17-10-2018 06:41	0	17-10-2018 11:07	731	17-10-2018 15:25	469
17-10-2018 06:58	5	17-10-2018 11:17	749	17-10-2018 15:35	439
17-10-2018 07:08	24	17-10-2018 11:27	765	17-10-2018 15:45	404
17-10-2018 07:18	52	17-10-2018 11:38	770	17-10-2018 15:56	365
17-10-2018 07:28	82	17-10-2018 11:49	768	17-10-2018 16:06	332
17-10-2018 07:39	117	17-10-2018 11:59	788	17-10-2018 16:16	293
17-10-2018 07:49	158	17-10-2018 12:09	788	17-10-2018 16:27	260
17-10-2018 08:00	209	17-10-2018 12:20	796	17-10-2018 16:37	219
17-10-2018 08:10	248	17-10-2018 12:30	791	17-10-2018 16:47	188
17-10-2018 08:20	283	17-10-2018 12:40	793	17-10-2018 16:57	149
17-10-2018 08:31	320	17-10-2018 12:51	788	17-10-2018 17:08	110
17-10-2018 08:41	355	17-10-2018 13:01	772	17-10-2018 17:18	70
17-10-2018 08:51	387	17-10-2018 13:11	768	17-10-2018 17:29	42
17-10-2018 09:02	427	17-10-2018 13:21	767	17-10-2018 17:39	21
17-10-2018 09:12	459	17-10-2018 13:32	749	17-10-2018 17:49	1
17-10-2018 09:23	492	17-10-2018 13:42	730	17-10-2018 18:00	0
17-10-2018 09:33	520	17-10-2018 13:52	705	17-10-2018 20:43	0
17-10-2018 09:44	554	17-10-2018 14:02	689	17-10-2018 20:53	0
17-10-2018 09:54	580	17-10-2018 14:13	668	17-10-2018 21:04	0
17-10-2018 10:04	608	17-10-2018 14:23	638	17-10-2018 21:15	0
17-10-2018 10:15	635	17-10-2018 14:33	624	17-10-2018 21:25	0

time and inclined insolation W/m^2). Generally, three methods; Average, Rectangular, and Trapezoidal methods are used for instant cumulative inclined insolation analysis.

A. AVERAGE METHOD

Generally, to calculate the area under the curve, the average method is used. For example, irradiance data at a gap of 15 minutes =6+22+69+119+178+ ………. +145 =11457/43=266 W/m^2. Generation is available for 10.5 hours. So, multiply the W/m^2 with 10.5 will get sun power input in Wh/m^2. Divide it with 1000; it will be kWh/m^2. Therefore, irradiance (kWh/m^2) = (266*10.5)/1000 = 2.793kWh/m^2. For calculation of cumulative inclined insolation, Pyranometer data of insolation taken from the weather station from Rajasthan in Table 21. Pyranometer loggers provide instantaneous data in each 10-minute variation, if any error occurs in fetch data then the logger fetch data in the next minute [29][30].

In Fig. 3, a graph is shown between insolation (W/m^2) and Time (in a minute). So by the average method, the areas calculated are as shown by the graph. Here, average inclined insolation = 476.43 W/m^2 and time duration (from 6.58 to 17.49) = 10:51 Hours. So, cumulative inclined insolation is given as,

$$\text{cumulative inclined insolation} = \frac{282.5094(w/m^2)}{1000} \times (10 + \frac{16}{60})hrs \quad (1)$$

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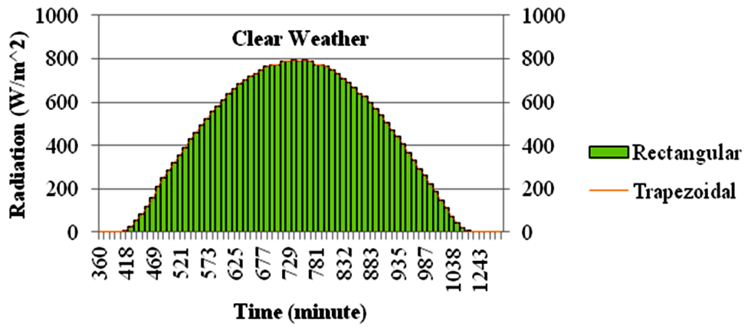

FIGURE 5. Graphical representation of cumulative insolation using rectangular & Trapezoidal method.

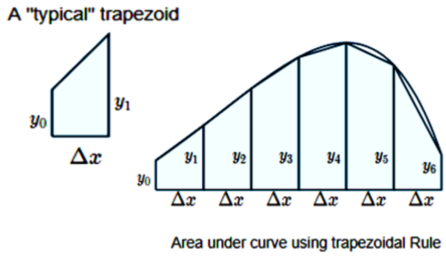

FIGURE 6. Graphical representation of cumulative radiation using trapezoidal method.

B. RECTANGULAR METHOD

To find more accurate areas under the curve, we use integration with the rectangular method. In this method, the interval of integration could be subdivided into '*n*' smaller intervals of equal lengths, and '*n*' rectangles would be used to approximate the integral; each smaller rectangle has the width of the smaller interval. The rectangle's height is the instant insolation provided by the Pyranometer and is continuous in that sample period. Within a fixed interval of integration, the approximation becomes more accurate as more rectangles are used; each rectangle becomes narrower, and the height of the rectangle better captures the values of the function within that interval. The total area of the curve is given by the sum of all rectangular areas [31-34]. For example,

$$\text{Total area}=\begin{cases}[(\text{area of Rectangle '1'})+\\(\text{area of Rectangle '2'})+\ldots\\+(\text{area of Rectangle 'n'})](\text{minute-watt/m}^2)\end{cases} \quad (2)$$

Total cumulative inclined Insolation

$$=\frac{\text{Total area under the curve}}{60\times1000}(\text{kwh/m}^2) \quad (3)$$

Fig.4 shows the rectangular method to calculate the area under the curve. Similarly, Fig.5 shows the graphical representation of cumulative insolation using the rectangular method. Pyranometer provides data in hour format, but for continuous integration of each 10 min area, a continuous parameter is needed.

C. TRAPEZOIDAL METHOD

Instead of rectangles, trapezoids (trapeziums) are used as shown in Fig.6. On X-axis time interval (in Minute) & on Y-axis Pyranometer readings (in W/m^2) have been considered. So total area is given by,

Total area

$$=\left\{\frac{1}{2}(\Delta X)(Y_1+Y_0)+\frac{1}{2}(\Delta X)(Y_2+Y_1)+\ldots.(minute-watt/m^2)\right. \quad (4)$$

Total cumulative inclined Insolation

$$=\frac{\text{Total area under the curve}}{60\times1000}(\text{kwh/m}^2) \quad (5)$$

TABLE 22. ERROR COMPARISON BETWEEN RECTANGULAR AND TRAPEZOIDAL METHOD (CLEAR WEATHER CONDITION)

Time in min	Inclined Irradiance	Inclined Irradiance	Percentage Error in Rectangular method	Time in min	Inclined Irradiance	Inclined Irradiance	Percentage Error in Rectangular method
	Rectangular Method	Trapezoidal Method			Rectangular Method	Trapezoidal Method	
360	0.0000	0.0000	0.00%				
370	0.0000	0.0000	0.00%	760	2.9460	3.0220	2.52%
381	0.0000	0.0000	0.00%	771	3.0905	3.1520	1.95%
391	0.0000	0.0000	0.00%	781	3.2191	3.2804	1.87%
401	0.0000	0.0007	100.00%	791	3.3471	3.4083	1.79%
418	0.0014	0.0031	54.67%	801	3.4750	3.5472	2.04%
428	0.0054	0.0095	42.73%	812	3.6123	3.6705	1.59%
438	0.0141	0.0206	31.72%	822	3.7340	3.7901	1.48%
448	0.0278	0.0389	28.60%	832	3.8515	3.9062	1.40%
459	0.0492	0.0618	20.37%	842	3.9663	4.0306	1.60%
469	0.0755	0.0954	20.85%	853	4.0888	4.1395	1.23%
480	0.1139	0.1335	14.72%	863	4.1951	4.2446	1.17%
490	0.1552	0.1778	12.70%	873	4.2991	4.3466	1.09%

500	0.2024	0.2330	13.17%	883	4.3989	4.4537	1.23%
511	0.2610	0.2893	9.77%	894	4.5034	4.5460	0.94%
521	0.3202	0.3511	8.81%	904	4.5931	4.6328	0.86%
531	0.3847	0.4257	9.64%	914	4.6769	4.7219	0.95%
542	0.4630	0.4996	7.33%	925	4.7629	4.7976	0.72%
552	0.5395	0.5867	8.06%	935	4.8361	4.8678	0.65%
563	0.6297	0.6711	6.17%	945	4.9034	4.9383	0.71%
573	0.7163	0.7695	6.91%	956	4.9703	4.9964	0.52%
584	0.8179	0.8640	5.34%	966	5.0257	5.0485	0.45%
594	0.9146	0.9630	5.03%	976	5.0745	5.0992	0.48%
604	1.0159	1.0770	5.67%	987	5.1222	5.1391	0.33%
615	1.1323	1.1851	4.46%	997	5.1587	5.1730	0.28%
625	1.2428	1.3088	5.04%	1007	5.1900	5.2011	0.21%
636	1.3686	1.4243	3.91%	1017	5.2148	5.2248	0.19%
646	1.4853	1.5425	3.71%	1028	5.2350	5.2398	0.09%
656	1.6051	1.6755	4.20%	1038	5.2467	5.2501	0.07%
667	1.7391	1.7988	3.32%	1049	5.2544	5.2553	0.02%
677	1.8639	1.9250	3.17%	1059	5.2579	5.2572	-0.01%
687	1.9914	2.0657	3.59%	1069	5.2580	5.2573	-0.01%
698	2.1326	2.2067	3.36%	1080	5.2580	5.2573	-0.01%
709	2.2734	2.3363	2.69%	1243	5.2580	5.2573	-0.01%
719	2.4047	2.4677	2.55%	1253	5.2580	5.2573	-0.01%
729	2.5361	2.6129	2.94%	1264	5.2580	5.2573	-0.01%
740	2.6820	2.7451	2.30%	1275	5.2580	5.2573	-0.01%
750	2.8138	2.8771	2.20%	1285	5.2580	5.2573	-0.01%
615	1.1323	1.1851	4.46%	997	5.1587	5.1730	0.28%
625	1.2428	1.3088	5.04%	1007	5.1900	5.2011	0.21%
636	1.3686	1.4243	3.91%	1017	5.2148	5.2248	0.19%
646	1.4853	1.5425	3.71%	1028	5.2350	5.2398	0.09%

TABLE 23. INCLINED RADIATION IN CLOUDY WEATHER OF DATE 27-11-2018.

Time	Inclined Insolation (W/m^2)	Time	Inclined Insolation (W/m^2)	Time	Inclined Insolation (W/m^2)
27-11-2018 00:00	0	27-11-2018 10:36	362	27-11-2018 16:00	147
27-11-2018 06:00	0	27-11-2018 10:49	367	27-11-2018 16:12	144
27-11-2018 06:10	0	27-11-2018 11:00	358	27-11-2018 16:25	107
27-11-2018 06:20	0	27-11-2018 11:11	346	27-11-2018 16:39	84
27-11-2018 06:30	0	27-11-2018 11:25	475	27-11-2018 16:52	45
27-11-2018 06:41	0	27-11-2018 11:36	455	27-11-2018 17:05	24
27-11-2018 06:52	0	27-11-2018 11:48	534	27-11-2018 17:19	15
27-11-2018 07:04	0	27-11-2018 12:00	374	27-11-2018 17:31	1
27-11-2018 07:14	5	27-11-2018 12:11	371	27-11-2018 17:44	0
27-11-2018 07:24	40	27-11-2018 12:25	411	27-11-2018 17:56	0
27-11-2018 07:35	89	27-11-2018 12:37	395	27-11-2018 18:10	0
27-11-2018 07:46	153	27-11-2018 12:47	520	27-11-2018 18:21	0
27-11-2018 07:56	158	27-11-2018 12:59	427	27-11-2018 18:35	0
27-11-2018 08:07	219	27-11-2018 13:10	388	27-11-2018 18:46	0
27-11-2018 08:18	320	27-11-2018 13:20	413	27-11-2018 18:57	0
27-11-2018 08:28	328	27-11-2018 13:35	582	27-11-2018 19:10	0
27-11-2018 08:38	353	27-11-2018 13:45	594	27-11-2018 19:21	0
27-11-2018 08:48	286	27-11-2018 13:55	270	27-11-2018 19:35	0
27-11-2018 08:58	204	27-11-2018 14:06	423	27-11-2018 19:46	0
27-11-2018 09:09	195	27-11-2018 14:20	256	27-11-2018 19:59	0
27-11-2018 09:19	249	27-11-2018 14:32	270	27-11-2018 20:10	0
27-11-2018 09:30	256	27-11-2018 14:45	242	27-11-2018 20:22	0
27-11-2018 09:41	355	27-11-2018 14:58	211	27-11-2018 20:34	0
27-11-2018 09:52	330	27-11-2018 15:10	195	27-11-2018 20:45	0
27-11-2018 10:03	462	27-11-2018 15:20	179	27-11-2018 20:56	0
27-11-2018 10:14	300	27-11-2018 15:33	193	27-11-2018 21:07	0
27-11-2018 10:25	337	27-11-2018 15:46	161	27-11-2018 21:19	0

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The drawback of rectangular method by using Table 22:

- The cumulative inclined insolation, calculated by the rectangular method, provides a final result of 5.2580 kWh/m^2.
- At the time of the start area calculation, rectangular method left the initial area of the graph.
- During the increment of the graph in Fig. 5, it left the area in the calculation, and during the decrement of the graph, it takes some extra area in the calculation. So, there is not the surety of this calculation is fully correct.

IV. ERROR COMPARISON FOR CUMULATIVE INCLINED INSOLATION

To investigate the cumulative inclined insolation using the error comparison concept on each time segment, Table 22 has been prepared using Eq.3 & 5. In this table results from rectangular and trapezoidal methods have been compared on each time segment during good weather and cloudy weather conditions.

- For estimation, live test data from Bikaner, Rajasthan has been chosen. From the comparison following results can be seen as From Table 22, during increment (from minute 401st to 760th) rectangular method left some area in the calculation, so it gives less value of calculation as compared to the trapezoidal method. Also, there is a continuous resultant error gap increase.
- During decrement of the graph (From minute 771st to1049th), in calculation rectangular method considers Some extra area, so difference b/w values of rectangular method and trapezoidal method continuously reduce. Also, there is a continuous resultant error gap decrease.
- Later in the 1059th minute, rectangular method considers some extra areas which give more error in the result.
- In a practical environment, each day of the year the weather is not clear, the maximum day it has a cloudy sky.
- So, graphs of insolation continuously fluctuate and rectangular method gives more error.

In this previous insolation data, there is continuous increment and decrement in insolation. But if there is variable insolation (due to cloud), at that time there is an error in the calculation of instant cumulative insolation in the rectangular method. In Table 23, cloudy weather data have been taken from a pyranometer situated in Bikaner, Rajasthan.

Average inclined insolation = 282.5094 W/m^2 and time duration (from 7.14 to 17.31) i.e. 10:16 Hours. So, cumulative inclined insolation is given as,

Cumulative Inclined Insolation

$$= \frac{282.5094\left(\frac{w}{m^2}\right)}{1000}(10+\frac{16}{60})hrs = 2.90043(\frac{kwh}{m^2}) \quad (6)$$

TABLE 24: ERROR COMPARISON BETWEEN RECTANGULAR AND TRAPEZOIDAL METHOD (BAD CLOUDY WEATHER CONDITION)

Time (min)	Rectangular Method	Trapezoidal Method	% Error in Rectangular Method	Time (min)	Rectangular Method	Trapezoidal Method	% Error in Rectangular Method
				790	1.9604	1.9897	1.48%
0	0.0000	0.0000	0.00%	800	2.0292	2.1141	4.02%
360	0.0000	0.0000	0.00%	815	2.1747	2.2121	1.69%
370	0.0000	0.0000	0.00%	825	2.2737	2.2841	0.46%
380	0.0000	0.0000	0.00%	835	2.3187	2.3476	1.23%
390	0.0000	0.0000	0.00%	846	2.3962	2.4268	1.26%
401	0.0000	0.0000	0.00%	860	2.4560	2.4794	0.95%
412	0.0000	0.0000	0.00%	872	2.5100	2.5349	0.98%
424	0.0000	0.0004	100.00%	885	2.5624	2.5840	0.83%
434	0.0008	0.0042	80.00%	898	2.6081	2.6246	0.63%
444	0.0075	0.0160	53.10%	910	2.6471	2.6557	0.32%
455	0.0238	0.0382	37.61%	920	2.6770	2.6960	0.71%
466	0.0519	0.0641	19.07%	933	2.7188	2.7344	0.57%
476	0.0782	0.0987	20.73%	946	2.7537	2.7703	0.60%
487	0.1184	0.1481	20.07%	960	2.7880	2.7994	0.41%
498	0.1770	0.2021	12.39%	972	2.8168	2.8266	0.35%
508	0.2317	0.2588	10.48%	985	2.8399	2.8489	0.31%
518	0.2905	0.3121	6.90%	999	2.8595	2.8629	0.12%

528	0.3382	0.3529	4.17%	1012	2.8693	2.8703	0.04%
538	0.3722	0.3895	4.44%	1025	2.8745	2.8749	0.01%
549	0.4079	0.4265	4.35%	1039	2.8780	2.8765	-0.05%
559	0.4494	0.4728	4.93%	1051	2.8782	2.8766	-0.06%
603	0.7067	0.7340	3.73%	1101	2.8782	2.8766	-0.06%
625	0.8234	0.8565	3.86%	1126	2.8782	2.8766	-0.06%
636	0.8898	0.9355	4.88%	1137	2.8782	2.8766	-0.06%
649	0.9693	1.0019	3.25%	1150	2.8782	2.8766	-0.06%
660	1.0350	1.0664	2.95%	1161	2.8782	2.8766	-0.06%
671	1.0984	1.1622	5.49%	1175	2.8782	2.8766	-0.06%
685	1.2092	1.2475	3.07%	1186	2.8782	2.8766	-0.06%
696	1.2926	1.3464	3.99%	1199	2.8782	2.8766	-0.06%
708	1.3994	1.4372	2.63%	1210	2.8782	2.8766	-0.06%
720	1.4742	1.5055	2.07%	1222	2.8782	2.8766	-0.06%
731	1.5423	1.5967	3.41%	1234	2.8782	2.8766	-0.06%
745	1.6382	1.6773	2.33%	1245	2.8782	2.8766	-0.06%
757	1.7172	1.7536	2.08%	1256	2.8782	2.8766	-0.06%
767	1.8038	1.8483	2.40%	1267	2.8782	2.8766	-0.06%
779	1.8892	1.9230	1.75%	1279	2.8782	2.8766	-0.06%

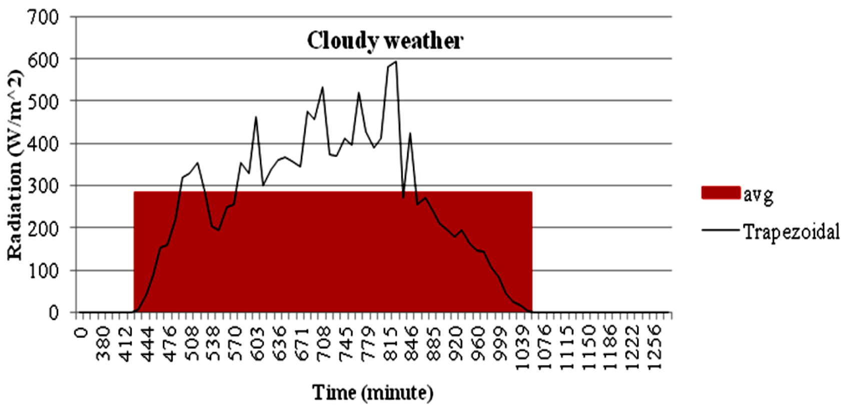

FIGURE 7. Insolation Data of cloudy weather (Average Method).

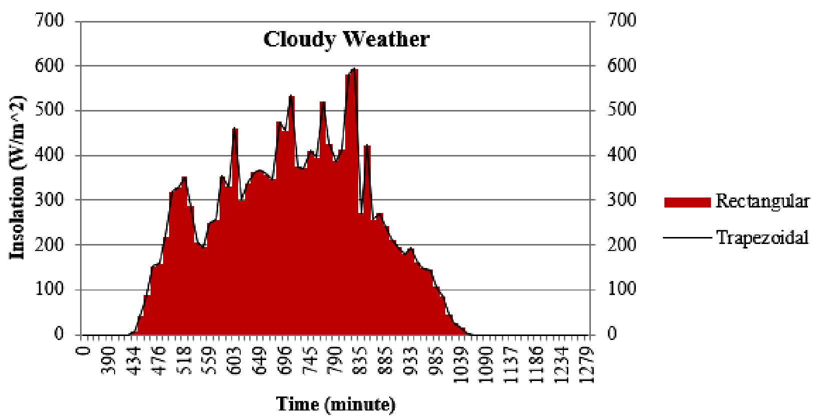

FIGURE 8. Insolation data of cloudy weather (Rectangular and Trapezoidal Method).

TABLE 25. RESULT COMPARISON OF CUMULATIVE INCLINED RADIATION.

Weather condition	Applied method		
	Average	Rectangular	Trapezoidal
CLEAR (Good)	5.16935	5.25802	5.25726
CLOUDY	2.90043	2.87818	2.87660

Fig. 7 shows the insolation data of cloudy weather (average method) and Fig.8 depicts insolation data of cloudy weather (rectangular and trapezoidal method).

From Table 24, the results are,

- Due to continuous fluctuation in the graph because of cloudy weather, there is uncertainty in the rectangular method.
- Firstly, from 424th minute to 559th minute, the error gap between rectangular and trapezoidal is reduced and later these gaps vary in an undefined manner and give less accurate results.

Similarly, from Table 25, the results are,

- The trapezoidal method gives better results in both clear and cloudy weather conditions, but the rectangular method and average method give more errors in calculation.
- For instantaneous calculation, the rectangular method gives more error from sunrise to noon, and later it adjusts the error from noon to evening.
- Cumulative inclined insolation is used to check solar plant efficiency (Performance Ratio), If we use the wrong values of insolation it gives the wrong result.
- With the help of the trapezoidal method, we can get more accurate values of cumulative inclined insolation that helps to check plant performance at any time instant.

V. CONCLUSION

Solar energy is renewable energy that is clean in nature and available in abundance. Solar insolation can be used to provide heat energy, light, and electrical power for domestic as well as industrial applications. In this case study, insolation estimation has been carried out over 14 airport locations. From the estimation, it has been evident that double seasonal tilt angle provides more global insolation as compared to fix tilt angle with a suitable azimuth angle and there is also a reduction in insolation level at fixed and double seasonal tilt angle if going away from the equator. It is also clear that after a certain limit of tilt angle, there will be a reduction in solar insolation if consider fixing the tilt angle. As estimation of cumulative inclined insolation plays an important role in global insolation analysis, three methods; Average, Rectangular, and trapezoidal have been used. From the analysis, it is found that during cloudy weather there is uncertainty in the rectangular method, but the trapezoidal method gives more accurate results in both clear and cloudy weather conditions than the rectangular & average method.

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