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A visual method to explore the climatic variables in a typical meteorological year

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Abstract
The irradiance and meteorological data of the location of installation is the chief requirement for estimating the influence of climate on the output of any solar energy convertor. The long term solar radiation datasets recorded at desired location with high temporal resolution are seldom available as the data logging require significant investment for deployment of robust measuring instruments in open environment. The accuracy of measurements is ensured by routine inspection and calibration which need expert vigilance and effort for quantification of uncertainty. The remote sensing satellites have solved this problem to a satisfactory level through constant improvements in algorithms which derive data from images taken at regular intervals in geostationary orbit. Thus, a satellite based global solar radiation database, such as PVGIS, which stands for Photovoltaic Geographical Information System, and provides an open interface for public to obtain the data free of cost, may be used to obtain typical meteorological data. A novel method for the visualization of air temperature, relative humidity, and global horizontal irradiance in TMY file is presented that can be helpful in the validation of data.

Keywords: Remote sensing, typical meteorological year, geographical information system, data visualization

Introduction
The world is going through a transition from conventional energy sources to renewable energy slowly and steadily. Before the global health crisis impacted the energy dynamics of the year 2020 and onwards, the global energy production and consumption were 617 EJ [1] and 581.51 EJ [2], respectively, in 2019. In the same year, the share of renewable energy sources in total electricity generation worldwide surpassed that of nuclear energy. It has been estimated that electricity accounts for 20% of world energy demand while 30% is consumed in the transport sector; but the remaining 50% energy is consumed in domestic and industrial heating applications and the renewables supply only 11% of this global heat demand [3]. The impetus for adoption of renewables in modern age mostly come from the issue of energy security challenged by unstable and rising prices of coal and crude oil. The issue of climate change from carbon emissions associated with production and use of fossil fuels have resulted in renewable energy targets for large economies of the world. Also, the non-renewable sources of energy have been deemed unsustainable numerous times when the proved reserves of coal, oil and gas are projected to deplete in near future at current rate of consumption.

The solar energy convertors are technological devices that convert the energy emitted by the sun in the form of electromagnetic radiation to other useful forms such as electricity, heat, and fuel [4]. Thus, sunlight is the fuel for all solar energy conversion technologies and the knowledge about its quality and reliability is essential for accurate analysis of system performance since the variability of the supply of sunlight presents the greatest uncertainty in a solar power plant's predicted performance [5].

The solar radiation data and other meteorological parameters are needed as input for performance prediction of solar energy convertors like photovoltaic (PV) panels and solar water heaters. Apart from influencing energy output, the climate also plays an important role in PV degradation [6]. As climate is the long-term weather pattern observed at a location which is usually averaged over 30 years, the relevant data is seldom available through actual site measurements.

In addition, the human economic development which results in global warming and air pollution, deviate the observed weather from climatic normal. Thus, it is assumed that 10 year averages can better predict the prevalent weather conditions of a location in accordance with the effect of human activities on climate in the near past. Hence, the data from a satellite based global solar radiation database, PVGIS, which stands for Photovoltaic Geographical Information System [7], are taken as sample. The images to estimate solar radiation in PVGIS are taken from METEOSAT geostationary satellites which cover Europe, Africa and Asia and the algorithms are developed with the collaboration of the Satellite Application Facility on Climate Monitoring (CM SAF) of European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

Materials and methods

For prediction of long-term performance of solar systems and energy analysis of buildings, a typical meteorological year (TMY) was conceived by researchers in last century [8] which represents average weather conditions in a year at a location obtained by applying statistical methods on long-term data and usually include (as in present TMY data) hourly values of solar and sky irradiance, air temperature, relative humidity, wind speed and direction, atmospheric pressure and other weather related parameters. These data are required for building heating simulations and can also be used to predict the performance of a solar energy conversion system during typical weather conditions (but not extreme ones). A sample day from the typical meteorological year data available from the version 5.2 of the PVGIS tool for the coordinates of Pantnagar is given in Table 1.

The hourly values in the TMY data from the PVGIS tool [9] are calculated from images taken at each hour of Coordinated Universal Time (UTC). Hence, the calculation of local standard time is not difficult given that the location of study (Pantnagar, UKD) follows the UTC+05:30 time offset which is also used as Indian Standard Time (IST). However, the calculation of solar time at the chosen location (geographical coordinates: 29.02°N, 79.48°E) from equation (1) needs some consideration as it includes equation of time (E) which takes into account the difference between apparent solar time and mean solar time due to non-uniformity in apparent daily motion of the Sun relative to stars. The equation of time is usually calculated from the precise Fourier series approximation developed from the nautical almanac data of 1950 in past century [10].

$$\text{Solar time} - \text{standard time} = 4(L_{st} - L_{loc}) + E$$

$$E = 229.2(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \quad (1)$$

Table 1: A sample day (1 January 2012) from the 2005-16 TMY Data corresponding to the coordinates of Pantnagar (29.02°N, 79.48°E)

Time (UTC) (YMD:HM)	T2m (°C)	RH (%)	G(h) (W/m^2)	Gb(n) (W/m^2)	Gd(h) (W/m^2)	WS10m (m/s)	WD10m (0°N ↻)
20120101:0000	12.69	87.54	0	0	0	0.96	58
20120101:0100	13.05	86.70	0	0	0	0.97	48
20120101:0200	13.41	85.86	0	0	0	0.98	52
20120101:0300	13.77	85.02	16	0	16	0.99	77
20120101:0400	14.12	84.18	44	0	44	1.00	115
20120101:0500	14.48	83.34	55	0	55	1.01	129
20120101:0600	14.84	82.50	124	0	124	1.02	152
20120101:0700	15.20	81.66	127	0	127	1.03	147
20120101:0800	17.28	73.95	498	391.81	269	1.17	161
20120101:0900	17.36	74.45	281	73.85	244	1.31	174
20120101:1000	17.00	76.90	162	24.29	153	1.38	201
20120101:1100	16.38	80.30	66	9.91	64	1.24	237
20120101:1200	15.36	85.75	0	0	0	1.66	271
20120101:1300	14.42	90.65	0	0	0	1.86	298
20120101:1400	13.92	92.65	0	0	0	2.00	325
20120101:1500	13.37	94.30	0	0	0	1.93	338
20120101:1600	13.04	94.45	0	0	0	1.93	345
20120101:1700	12.67	94.60	0	0	0	1.79	348
20120101:1800	12.23	95.25	0	0	0	1.59	347
20120101:1900	12.24	94.65	0	0	0	1.38	344
20120101:2000	12.68	93.25	0	0	0	1.24	341
20120101:2100	12.82	92.55	0	0	0	1.24	342
20120101:2200	12.71	92.80	0	0	0	1.17	338
20120101:2300	12.43	91.95	0	0	0	1.10	335

Key

UTC: Coordinated Universal Time
T2m: 2-m air temperature
RH: Relative humidity
G(h): Global irradiance on the horizontal plane
Gb(n): Beam/direct irradiance on a plane always normal to sun rays
Gd(h): Diffuse irradiance on the horizontal plane
WS10m: 10-m total wind speed
WD10m: 10-m wind direction

Results & Discussion

The straightforward visualization of variables in Table 1, such as global horizontal irradiance against time results in Fig. 1, which shows the intermittency of the solar resource at hourly resolution. It should be noted that the time axis is to scale as the nights are also included in Fig. 1 [11]. Although, this is the best way to visualize the variables in a TMY file without any loss of information, the analyst cannot compare the pattern of climatic variables in the months selected for TMY, which come from different years.

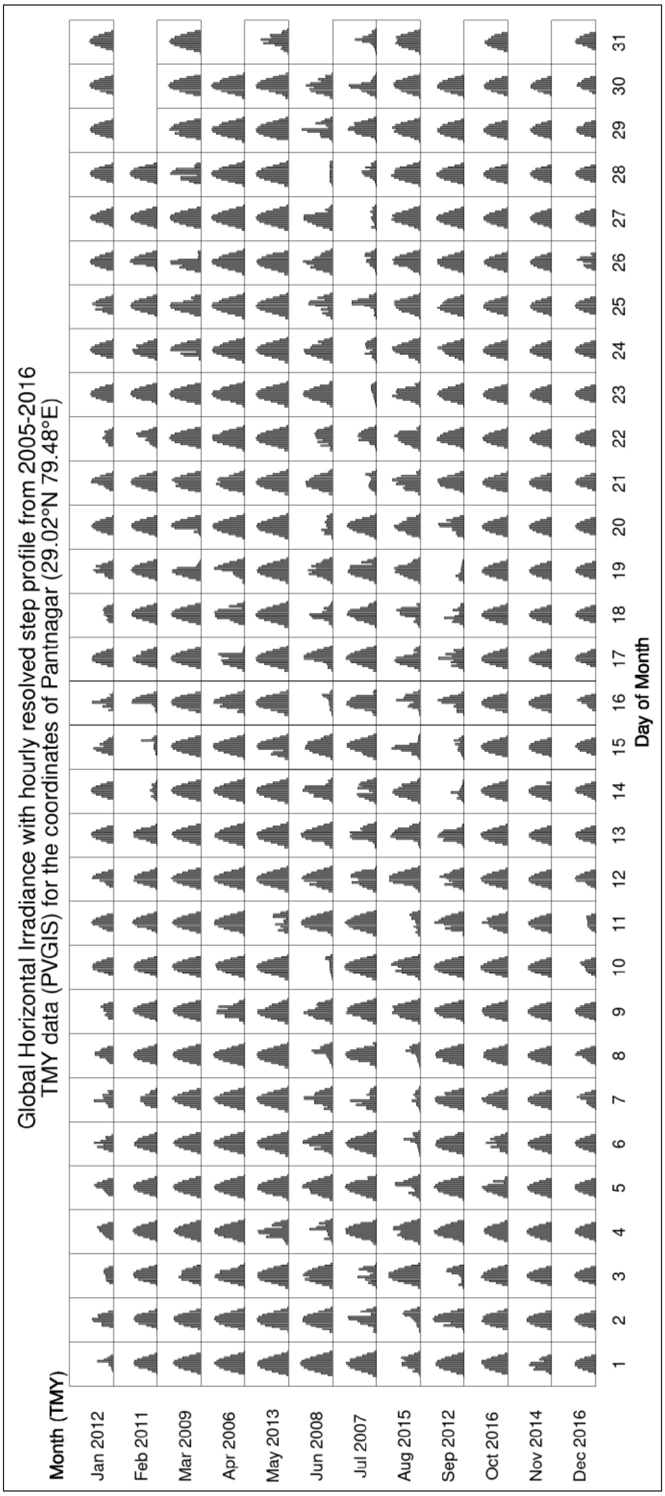

Fig 1: Caption in figure title

The box-and-whisker plots developed by John Tukey (Figs. 2-4) are used here to elegantly show the distribution of data during the month at respective hour of the day. The box represents all the points which lie in the interquartile range (middle 50% points) of the data recorded at that particular hour during the month. The median of the data is represented by the parting line inside the box. The points which lie in the two remaining quarters of the data are above and below the box. The whiskers indicate the most extreme data point on each side of the box which is within 1.5 times the height of the box. The separately drawn points on the plot are the outliers in the data which indicate considerable deviation from normal.

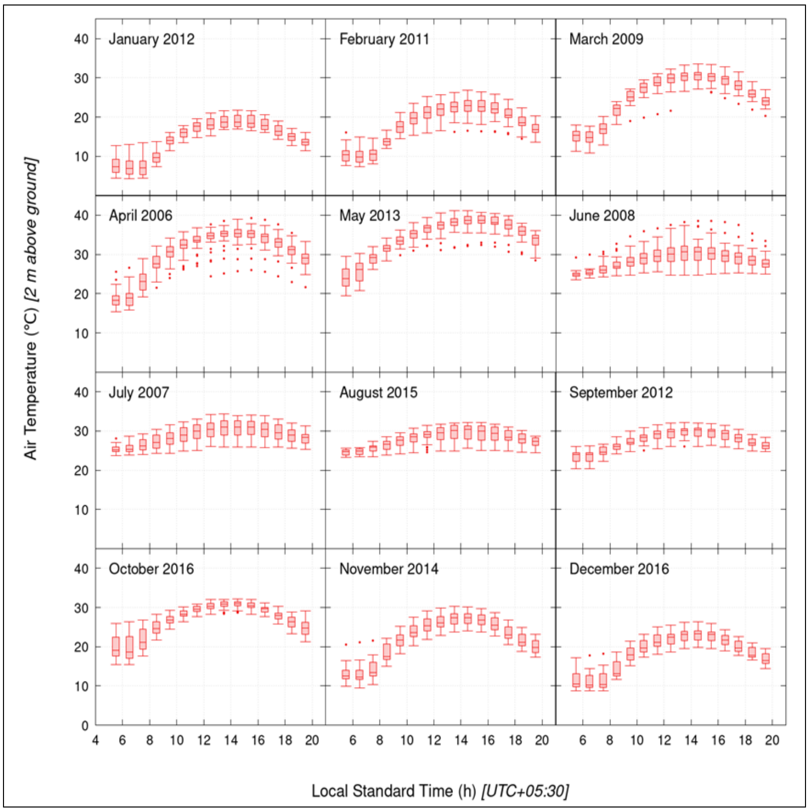

Fig 2: Box plots showing monthly variation of air temperature at 2m above ground (ambient temperature) for different hours of day in TMY data obtained from PVGIS corresponding to the coordinates of Pantnagar (29.02°N, 79.48°E)

The air temperature at Pantnagar follow the seasonal variation observed in northern hemisphere and remains above the freezing point of water (0℃) even in the coldest winter. The temperature follows a sine wave through the day and peaks near 15:00 hours (3 PM). Most anomalies in temperature data from normal occur in the period from April to June which may be attributed to sudden drop in temperature due to storms in April and May, as shown in Fig. 2. An increase in intensity of sunlight after rain (due to a clear atmosphere) might be the reason of high temperature outliers in the boxplots for June.

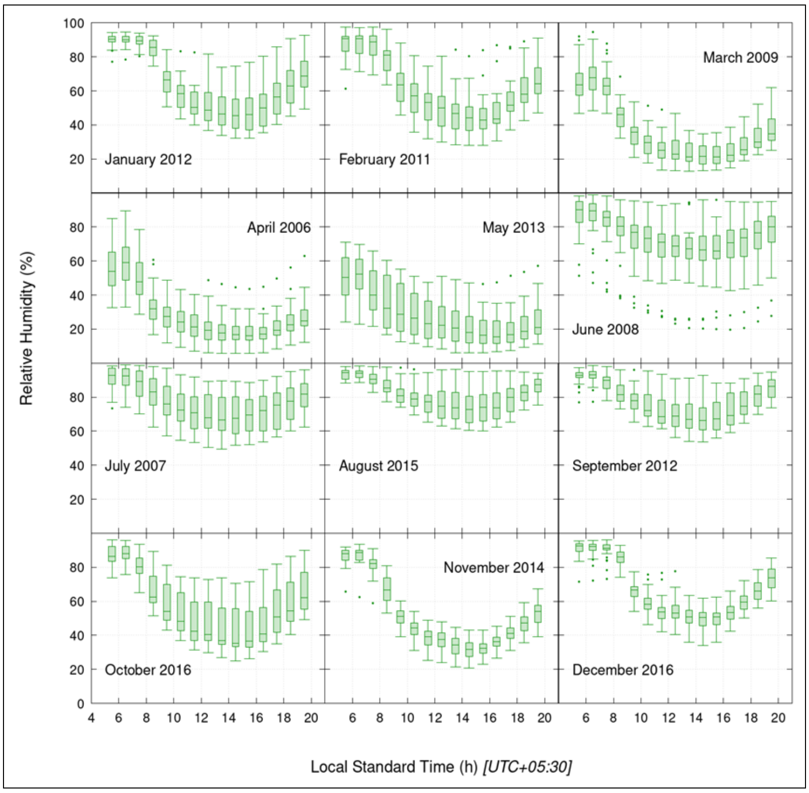

Fig 3: Box plots showing monthly variation of relative humidity for different hours of day in TMY data obtained from PVGIS corresponding to the coordinates of Pantnagar (29.02°N, 79.48°E)

The solar irradiance through the day increases air temperature which results in a corresponding decrease in relative humidity when compared with the high relative humidity corresponding to the low ambient temperature at morning and evening, as shown in Fig. 3. The period from June to September is the most humid time of the year due to the evaporation of water (by solar heat), which has been accumulated on earth from heavy rains in monsoon. The driest month of summer is April while that of winter is November.

It is clear from Fig. 4 that except the period of monsoon (June, July, August, and September) and foggy winter (December and January), low global horizontal irradiance (overcast condition) is an anomaly at Pantnagar.

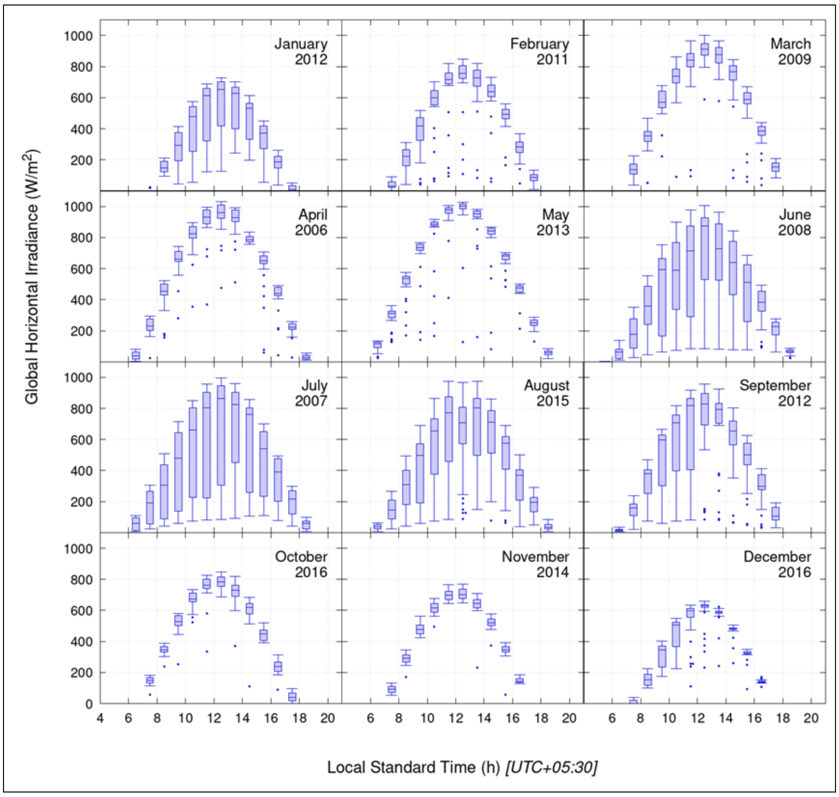

Fig 4: Box plots showing monthly variation of global horizontal irradiance for different hours of day in TMY data obtained from PVGIS corresponding to the coordinates of Pantnagar (29.02°N, 79.48°E)

Conclusions

The use of box-and-whisker plots allows concise exploration of the variables of interest in typical meteorological year (TMY) dataset against the time of day, categorized by months. The TMY data of Pantnagar obtained through PVGIS Online tool do not show any discrepancies from locally observed climate. The median values of climatic variables obtained through the exploratory data analysis of TMY data may be used as nominal values for the respective month for the sensitivity analysis of the performance of solar energy convertors as this is the best approach to represent the typical climatic conditions of months.

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