25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

SIZING OF A PHOTOVOLTAIC SYSTEM USING THE TYPICAL METEOROLOGICAL YEAR OF ITAPEVA - SÃO PAULO

Gustavo Bulgraen dos Santos
Elí Wilfredo Zavaleta-Aguilar
São Paulo State University (Unesp), Campus of Itapeva, Rua Geraldo Alckmin 519, 18409-010 Itapeva, São Paulo, Brazil.
gustavo.bulgraen@unesp.br; eli.zavaleta@unesp.br

Abstract.
The weather of a given region varies from year to year. The knowledge of a local climate representative year of a historical series allows the evaluation, design, planning and operation of renewable-energy power plants as well as buildings energy simulation. Therefore, this work is dedicated to evaluating the typical meteorological year (TMY) of the Itapeva city, a São Paulo state southwest Brazilian municipality. For this, the Sandia National Laboratories method was used for an 11 year-long data series (global radiation, dry bulb temperature, wind speed and dew point temperature) supplied by INMET (National Institute of Meteorology of Brazil). The results indicate that the Itapeva typical meteorological year is composed of the months: January 2011, February 2009, March 2010, April 2008, May 2014, June 2017, July 2013, August 2016, September 2012, October 2009, November 2014 and December 2016. In addition, using the TMY data, it was possible to size a photovoltaic system for a São Paulo state average electric consumption residence.

Keywords: *Typical meteorological year, Sandia method, solar potential, photovoltaic system.*

1. INTRODUCTION

Current society requires high energy demand for its daily activities. The energy production is based mainly on fossil fuels such as coal, oil and natural gas which have significant environmental impacts, as global warming, acid rain and air pollution, that can result in asthma, chronic obstructive pulmonary disease or lung cancer (Guarieiro, Vasconcellos and Solcib, 2011). Therefore, renewable energy, such as solar (thermal and photovoltaic), wind and hydroelectric, appears as alternative (Goldemberg and Lucon, 2007).

Solar energy projects require of the typical local climatology knowledge that can be obtained from typical meteorological year (TMY) methods. Those methods analyze the local climatic variation of a period, generally long term, and give a representative typical year as result (Weide et al., 2012).

There are several methods for calculating a typical weather year, which are detailed in Wilcox and Marion (2008). Skeiker et al. (2007) indicate that the Sandia method presents better results in several places around the world. Therefore, this work was developed applying this method for determining of the typical meteorological year of the Itapeva-SP city (23º 58º 53º S, 48º 53º07º W). In this city there is a weather station that recorded data since January 1st, 2007 and the data analyzed in this work were from that date until December 31st, 2017, that is, a 11 year- period, unlike to 30-year data proposed by Hall et al. (1978). Other works, such as Weide et al. (2012) that used a database of 10 years and Bre and Fachinotti (2014) that used data from 2000 and 2013, show the effectiveness of TMY determination even with a database of less than 30 years.

The typical meteorological year is a tool used to evaluate and model the thermal behavior of buildings and the performance of solar energy devices. It is also used in energy efficient building simulation, since that modern ones consume a lot of energy, while they are heated, cooled and illuminated, therefore, sustainable buildings are energy autonomy (producing energy onsite by themselves) and have better thermal and lighting comfort.

One of the most notable applications of TMY is the design of photovoltaic systems which are based on the transformation of solar irradiation into electrical energy by means of photovoltaic cells which are made from semiconductor materials (usually silicon). These devices do not require high solar radiation to work, so energy production, even far of its maximum efficiency point, is continuous throughout the year in a country as Brazil. Photovoltaic electric energy production presents advantages such as: being renewable, does not emit any noise, its onsite implantation eliminates the use of generating centers and energy transport, furthermore, those systems need of minimum maintenance.

2. OBJECTIVES

The goal of this work is to obtain the Itapeva-SP city typical meteorological year as a function of meteorological data (global radiation, dry bulb temperature, wind speed and dew point temperature) obtained from the National Institute of Meteorology of Brazil (INMET) (INMET, 2018). Also, this work aims to size a photovoltaic system for a São Paulo state average electric consumption residence by means of the typical meteorological year data.

3. METHODOLOGY

3.1 Typical meteorological year

According to Hall et al. (1978), the method Sandia is used to select a characteristic month of the local climatology for each one of the 12 months of the year, taking into account the meteorological variables: bulb temperature, dew point temperature, global radiation and wind speed. For this, the Finkelstein-Schafer statistic is used, which evaluates the similarity of each specific month with the data set of the whole period, for the same month, based on the absolute difference between the two cumulative distribution function (CDF), as shown in Eq. (1).

$$FS_x(y,m)=\frac{1}{N}\sum_{i=1}^{N} |CDF_m(X_i)-CDF_{y,m}(X_i)| \tag{1}$$

Where CDF_m is the cumulative distribution function of the month m of all years and $CDF_{y,m}$ is the cumulative distribution function of the month m and year y, X_i is the index used for the meteorological variables and N is the number of days of the CDF. Afterwards, a weighted sum WS (according to Eq. (2)) is evaluated to select the possible months of the TMY.

$$WS(y,m)=\frac{1}{M}\sum_{i=1}^{M} WF_x.FS_x(y,m) \tag{2}$$

Where M is the number of meteorological variables considered and WF_x is the weighting factor for each variable x that were based on those suggested by Argiriou et al. (1991) (Tab. 1), being selected according to their influence on global radiation, for each variable x. Finally, as suggested by Weide et al. (2012) and Bre and Fachinotti (2016) the 5 candidate months with lower WS are selected (for each of the 12 months of the year). The candidate with smaller WS is chosen to compose the typical meteorological year.

Table 1. Weighting factors used in the Sandia National Laboratories method (Skeiker, 2007)

Global Radiation	Mean dry bulb temp.	Max. dry bulb temp.	Min. dry bulb temp.	Mean wind speed	Max. wind speed	Mean dew temp.	Max. dew temp.	Min. dew temp.
0.5	0.08333	0.04167	0.04167	0.08333	0.08333	0.08333	0.04167	0.04167

3.2 Sizing a photovoltaic system

There are several methods for sizing photovoltaic systems, such as, the intuitive, the numerical, the analytical, the hybrid and the artificial intelligence method. This work considers the intuitive method since it is not the goal of this paper deal with more specific analyzes. Reader is directed to paper of Khatib, Ibrahim and Mohamed (2016) for a comprehensive review of sizing methods. The intuitive method of Buresch (1983) initially evaluates the peak sun-hours (*PSH)* of each month (Eq. 3), defined as the number of hours that the solar irradiance is equivalent to 1.0 kW/m². For this, it is necessary to find the monthly average daily radiation ($\overline{H}$) which is equal to the typical month global radiation divided by the number of days of each month.

$$PSH=\frac{\overline{H}}{1.0} \tag{3}$$

Finally, the photovoltaic system power (P) is obtained by Eq. (4).

$$P=\frac{\overline{DC}}{\overline{PSH}\,\eta} \tag{4}$$

Where $\overline{DC}$ is the average daily electric power consumption, $\overline{PSH}$ is the daily average peak sun hours and η is the system efficiency, which following Ekici and Kopru (2017) consider losses due to: shading, dust and dirt, reflection, spectral, irradiation, thermal (temperature), array mismatch, DC cable, inverter and AC cable as shown schematically in Fig. 1.

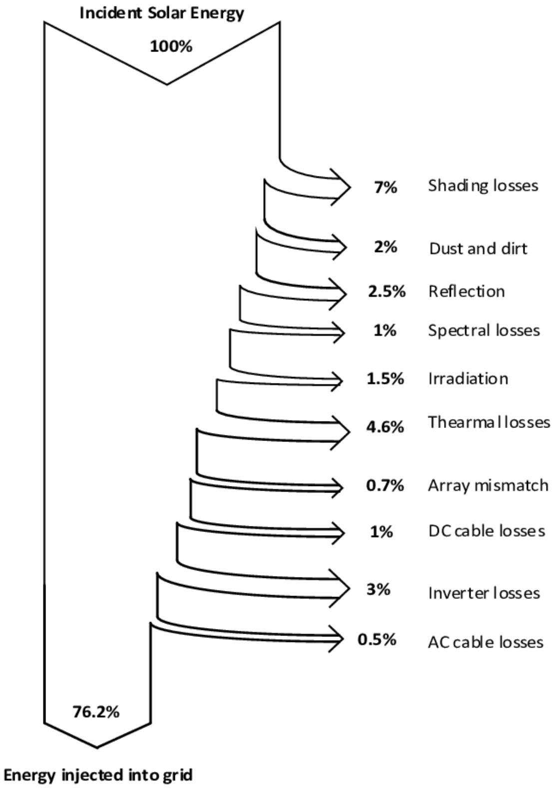

Figure 1. Photovoltaic system losses (Ekici and Kopru, 2016).

4. RESULTS

4.1 Typical meteorological year

During the analysis of the INMET data (INMET, 2018), some incomplete data were found in the following months: August, October and November of 2010, December of 2011, January, February and March of 2012, March and July 2014 and April and May 2015, such months were disregarded. The *FS* values calculated for each month of the 11-year period, for the global radiation and the average dry bulb temperature, are presented in Tab. 2 and Tab. 3, respectively and Tab. 4 shows the *WS* (weighted sum), used to select the TMY candidate month.

Table 2. *FS* statistics value for global solar radiation.

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
January	0.096	0.090	0.111	0.098	0.061		0.051	0.162	0.204	0.038	0.109
February	0.103	0.064	0.053	0.126	0.070		0.040	0.135	0.071	0.053	0.073
March	0.318	0.063	0.060	0.080	0.205		0.151		0.135	0.075	0.110
April	0.057	0.057	0.124	0.036	0.048	0.069	0.270	0.039		0.202	1.092
May	0.028	0.039	0.042	0.044	0.063	0.059	0.048	0.028		0.127	0.048
June	0.169	0.069	0.441	0.199	0.144	0.131	0.355	0.364	0.386	0.060	0.065
July	0.054	0.240	0.196	0.081	0.054	0.096	0.057		0.128	0.113	0.185
August	0.078	0.088	0.054		0.049	0.203	0.065	0.096	0.090	0.056	0.063
September	0.066	0.053	0.150	0.084	0.144	0.061	0.425	0.071	0.272	0.121	0.291
October	0.075	0.124	0.034		0.095	0.091	0.080	0.160	0.034	0.035	0.175
November	0.044	0.084	0.033		0.093	0.047	0.351	0.027	0.343	0.046	0.020
December	0.118	0.162	0.050	0.051		0.083	0.212	0.063	0.130	0.041	0.313

Table 3. *FS* statistics value for average temperature.

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
January	0.053	0.202	0.168	0.064	0.121		0.181	0.233	0.285	0.055	0.080
February	0.042	0.181	0.047	0.174	0.109		0.116	0.109	0.111	0.079	0.086
March	0.224	0.052	0.108	0.041	0.140		0.110		0.110	0.065	0.069
April	0.193	0.084	0.053	0.045	0.050	0.043	0.372	0.076		0.448	0.060
May	0.086	0.411	0.083	0.029	0.062	0.091	0.066	0.080		0.103	0.105
June	0.290	0.051	0.166	0.056	0.070	0.076	0.341	0.233	0.501	0.139	0.043
July	0.112	0.129	0.034	0.171	0.143	0.096	0.054		0.081	0.133	0.042
August	0.075	0.104	0.028		0.082	0.156	0.061	0.059	0.222	0.059	0.071
September	0.219	0.171	0.084	0.065	0.138	0.120	0.372	0.077	0.242	0.093	0.299
October	0.140	0.051	0.065		0.028	0.184	0.038	0.146	0.110	0.078	0.082
November	0.080	0.124	0.317		0.141	0.024	0.277	0.068	0.259	0.035	0.092
December	0.049	0.136	0.050	0.043		0.281	0.170	0.065	0.073	0.056	0.396

Table 4. *WS* index for the 11-year period.

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
January	0.095	0.125	0.115	0.097	0.051		0.096	0.147	0.175	0.055	0.108
February	0.090	0.096	0.059	0.115	0.067		0.061	0.147	0.070	0.099	0.090
March	0.226	0.078	0.067	0.064	0.156		0.110		0.114	0.072	0.096
April	0.112	0.057	0.102	0.061	0.068	0.058	0.330	0.070		0.237	0.587
May	0.061	0.100	0.058	0.054	0.075	1.304	0.079	0.054		0.101	0.078
June	0.147	0.092	0.288	0.147	0.122	0.124	0.370	0.279	0.398	0.073	0.058
July	0.082	0.179	0.168	0.113	0.074	0.089	0.064		0.142	0.100	0.141
August	0.095	0.109	0.075		0.085	0.155	0.076	0.076	0.104	0.069	0.093
September	0.087	0.103	0.166	0.081	0.143	0.077	0.343	0.086	0.298	0.104	0.239
October	0.100	0.116	0.061		0.074	0.098	0.082	0.136	0.093	0.069	0.150
November	0.070	0.106	0.136		0.121	0.058	0.312	0.040	0.337	0.053	0.080
December	0.127	0.185	0.086	0.066		0.164	0.174	0.068	0.148	0.049	0.334

From Tab. 4 it is possible to note that the typical months are composed by: January 2011, February 2009, March 2010, April 2008, May 2014, June 2017, July 2013, August 2016, September 2012, October 2009, November 2014 and December 2016. Once, the months of the typical meteorological year are obtained it is possible to know the monthly radiation and the typical monthly average temperature over a year, these values are indicated in Fig. 2 and 3, respectively.

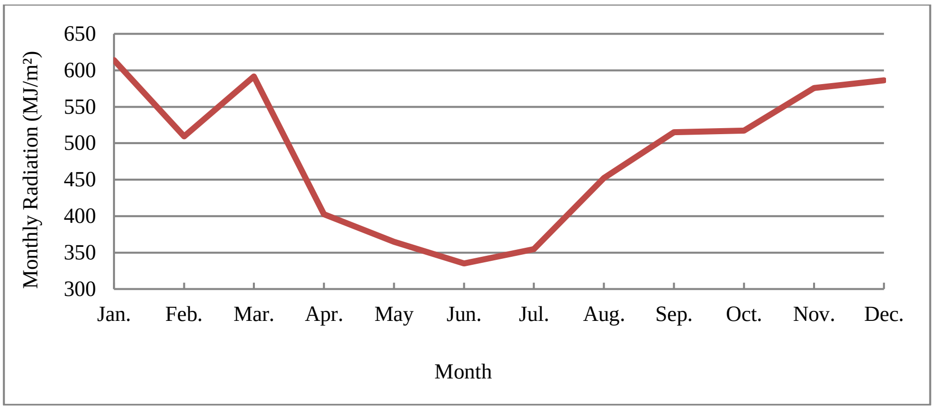

Figure 2. Monthly global radiation in the typical months of Itapeva-SP.

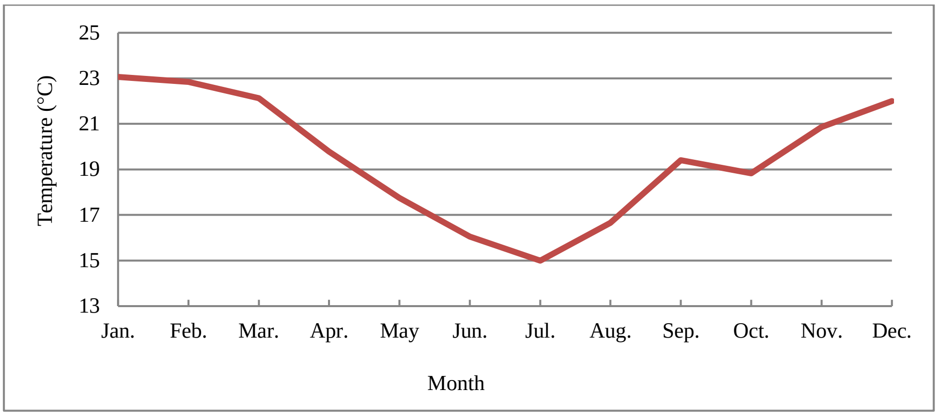

Figure 3. Average dry bulb temperature.

4.2 Sizing a residential photovoltaic system

Table 5 shows the average daily horizontal global radiation in Itapeva-SP city, which was obtained from the monthly global radiation (Fig. 2) divided by the number of days of each month.

Table 5. Average daily global radiation for each month of the TMY in the horizontal plane (kWh/m²) in Itapeva-SP

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
5.50	5.06	5.30	3.37	3.27	3.10	3.18	4.05	4.77	4.64	5.33	5.25

The peak sun hours for each month were evaluated according to Eq. (3) and the results are shown in Tab. 6, giving an average value of 4.40. On the other hand, according to the Brazilian Energy Research Company (EPE, 2017), the São Paulo state average electric consumption residence in 2016 was of 191.3 kWh/month (6.37 kWh/day). Finally, the required photovoltaic system power for that residence, considering photovoltaic panel positioned in the horizontal plane, will be of 1.9 kWp.

Table 6. Peak sun hours (h/day) for each month of the TMY in Itapeva-SP

Mês	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
HSP (0°)	5.50	5.06	5.30	3.37	3.27	3.10	3.18	4.05	4.77	4.64	5.33	5.25
HSP (23°)	5.15	5.00	5.66	4.27	4.00	3.98	4.00	4.79	5.25	4.74	5.08	4.89

When the photovoltaic panels are inclined from the horizontal reference an angle equal to the local latitude, it is possible they absorb more radiation energy. Thus, using the Radiasol program (UFRGS, 2012) and the horizontal global radiation it is possible to determine the inclined (23°, in this case) PSH. This value is shown in Table 6. Considering this inclination, the required power decreases to 1.76 kWp. The photovoltaic system of 1.76 kWp will produce an average monthly energy indicated in Fig. 4.

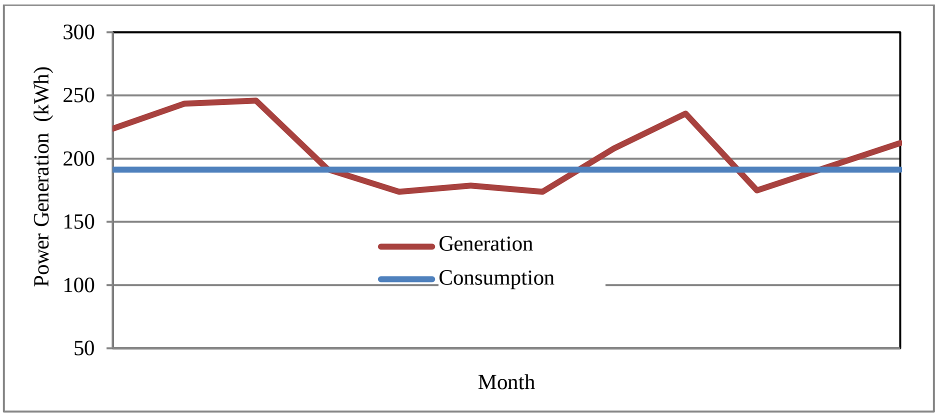

Figure 4. Average monthly photovoltaic energy generation and consumption.

Figure 4 shows that in some months the generation of energy exceeds the electric energy consumption required (191 kWh). It is important to point out that there are methods for storing surpluses energy, for example in batteries, usually used in OFF-grid system, or even obtaining energy credits of the power distribution company in ON-grid systems. Still, the required power could be reduced to 1.49 kWp if it is considered the mandatory minimum monthly residential consumption (ANEEL, 2010).

5. CONCLUSION

This work evaluated the typical meteorological year of the Itapeva - SP city, following the Sandia method, which is constituted by the following typical months: January 2011, February 2009, March 2010, April 2008, May 2014, June 2017, July 2013, August 2016, September 2012, October 2009, November 2014 and December 2016. The TMY is an important tool since it allows to obtain enough information of the local (or even in nearby cities) weather to simulate renewable-energy power plants efficiently. Throughout the study, data tables were developed for the TMY implementation, which allows update the database. Using the typical meteorological year radiation data was possible to evaluate the photovoltaic system power for a São Paulo state average electric consumption residence.

6. ACKNOWLEDGEMENTS

The first author thanks to PROPe – UNESP for the personal support.

7. REFERENCES

ANEEL, 2010. “Resolução Normativa Nº 414 de 9 de setembro de 2010”. Agência Nacional de Energia Elétrica. 25 Oct. 2016 < http://www.aneel.gov.br>.

Argiriou A., Balaras C., Dascalaki E., Gaglia A., Gountelas G., Moustris K., Santamouris M. and Vallindras M., 1991. “Energy audits in public and commercial buildings in Greece”, In *Proceedings of the 3rd European symposium: soft energy action at the local level*, Chios, Greece.

Bre, F. and Fachinotti, V.D., 2014. “Generación del año meteorológico típico para la ciudad de Santa Fe en la Región litoral Argentina”. *Avances en Energías Renovables y Medio Ambiente*, Vol. 18, pp. 11.01-11.08.

Bre, F. and Fachinotti, V.D., 2016. “Generation of typical meteorological years for the Argentine Littoral Region”. *Energy Build*, Vol. 129, pp. 432–444.

Buresch M., 1983. *Photovoltaic energy systems*. McGraw–Hill, New York.

Ekici, S. and Kopru, M.A., 2017. "Investigation of PV System Cable Losses", *International Journal of Renewable Energy Research*, Vol. 7, No. 2, pp. 807–815.

EPE, 2017. “Anuário Estatístico de Energia Elétrica 2017 ano base 2016”, Empresa de Pesquisa Energética. 12 May 2019 < https://ben.epe.gov.br >.

Goldemberg, J. and Lucon, O., 2007. “Energia e meio ambiente no Brasil”. *Estudos Avançados*, Vol. 21, No. 59, pp. 7-20.

Guarieiro, L.L.N., Vasconcellos, P.C. and Solci, M.C., 2011. “Poluentes atmosféricos provenientes da queima de combustíveis fósseis e biocombustíveis: uma breve revisão”. *Virtual Química*, Vol. 3, No. 5, pp. 434 – 445.

Hall, I.J., Prairie, R.R., Anderson, H.E. and Boes, E.C., 1978. “Generation of a typical meteorological year”. In: *Analysis for solar heating and cooling*, San Diego, United States.

INMET, 2018. “Dados metereológicos de estações automáticas”, Instituto Nacional de Meteorologia. 23 May 2018 <www.inmet.gov.br>.

Khatib, T., Ibrahim, I.A, and Mohamed, A., 2016. “A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system”, *Energy Conversion Management*, Vol. 120, pp. 430–448.

Pinho J.T. and Galdino M.A., 2014. *Manual de engenharia para sistemas fotovoltaicos*. Rio de Janeiro.

Skeiker, K., 2007. “Comparison of methodologies for TMY generation using 10 years data for Damascus, Syria”, *Energy Conversion and Management*, Vol. 48, pp. 2090–2102.

UFRGS, 2012. “Programa RADIASOL”, Laboratório de Energia Solar, 2012.

Weide E., Ramos F., Bueno E. and Schuch N., 2012. “Determinação de um ano meteorológico típico para Florianópolis-SC”. In: *Congresso Brasileiro de Energia Solar – CBENS.* São Paulo, Brazil.

Wilcox, S., and Marion, W., 2008. Users Manual for TMY3 Data Sets. Technical Report NREL/TP-581-43156, NREL Lab., Golden, United States.

8. RESPONSIBILITY NOTICE