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Use of monthly average solar radiation data for assessing the efficiency of a photovoltaic array

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Abstract. Efficient solar energy installations depend largely on the availability of meteorological and geographical data (geographical coordinates, solar radiation, ambient temperature, wind speed) and the technical characteristics of the photovoltaic arrays. Usually, both, radiation and meteorological measurements are based on hourly surface observational data, not always easily accessible therefore requiring enormous memory capacity to be processed. From a practical point of view, this work investigated whether or not monthly average resource data can be used to assess the efficiency of the photovoltaic conversion (and thus the electrical energy obtained from this conversion) whenever hourly-based meteorological data are scarce or unreliable. Photovoltaic efficiency was calculated from predicted temperature of the cell by making use of classical analytical models of photovoltaic conversion. Calculations performed based on monthly average solar resource data reproduced within 0.5 K the temperature of the photovoltaic array and within 6% the total amount of energy converted as compared to hourly average solar resource data made available by official solar radiation and meteorological data bases.

Keywords: Solar energy; photovoltaic conversion; cell temperature; hourly average solar resource data; monthly average solar resource data

1 Introduction

Over the last fifty years the technology of photovoltaic cells for generating electricity experimented dramatic changes. The first practical cells manufactured from single-crystal wafers of semiconductor-grade silicon (1954) converted about 6% of the total incident sunlight into electrical power. As a result of innovative research leading to the Si cell technology, nowadays, polycrystalline cells may attain over 23% efficiency under direct sunlight and almost 30% under sunlight concentrated by a factor of a few hundred times [1]. Commercial cells are moving toward 20% efficiency yielding multicell modules of about 15% efficiency [2]. Unlike fossil fuel or nuclear power plants, operation and maintenance costs of solar plants are usually quite small. With improved capacity of large-grained polycrystalline materials to absorb light, photovoltaic conversion (PV-conversion), promise to become, from the technical and economic perspectives, an attractive and competitive alternative source of renewable energy. Indeed, these remarkable innovations have reduced prices of photovoltaic conversion from USD 1 million/kW to a few USD/kW in the course of the last 50 years [2].

Solar managers, designers, building architects, engineers and renewable energy analysts often question manufacturers of photovoltaic arrays on the accuracy of the technical information reported for their commercial photovoltaic panels.

Solar resource data – critical to installation planning and siting – are always associated with substantial global, direct, and diffuse mass of information. Wind speed/direction and other meteorological data – that also affect the efficiency of the photovoltaic conversion – are, likewise, associated with massive data and comprehensive collections of solar gridded maps. Calculation of the energy obtained from the photovoltaic conversion is normally troublesome. Usually it requires access to and processing of massive meteorological and solar databases, laboratory certification of the panel, and complex calculation of the substrata cell temperature. As it will be discussed in this paper, the cell temperature is a prerequisite for the calculation of the efficiency of the photovoltaic conversion needed to appraise the electrical energy generated.

The aim of this work is twofold: to investigate whether or not average monthly data could be used to assess the efficiency of the photovoltaic conversion, (a useful shortcut to replace hourly average meteorological data not always available) and (ii) to assess if average monthly data can be used as an strategy to smooth out higher uncertainty associated with hourly average meteorological data of recurrent low quality.

2 Maximum power photovoltaic efficiency and energy conversion

In terms of electrical quantities, Figure 1 depicts the typical behaviour of a photovoltaic array based on which one

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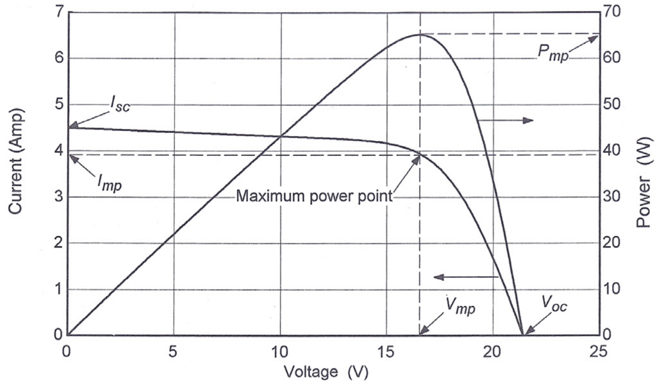

Fig. 1. Typical curve representing the electrical parameters of the photovoltaic conversion Fonte: Duffie and Beckman (2006) [3].

can define the so called *efficiency of the photovoltaic* at maximum power (η_{mp}).

The maximum power photovoltaic efficiency η_{mp} can be calculated by equation (1); i.e.: by the ratio between the electric energy obtained from the photovoltaic conversion ($I_{mp}V_{mp}$) and the local value of the incident solar radiation G_T, usually made available by government organizations responsible for the custody of official solar radiation databases. Alternatively, this maximum power photovoltaic efficiency η_{mp} can be calculated from the substrata cell temperature that also depends on input meteorological data (solar radiation, ambient temperature and wind speed) measured at the geographical coordinates (latitude and longitude) where the photovoltaic array is installed.

$$\eta_{mp} = \frac{I_{mp}\,V_{mp}}{A_c\,G_T} \tag{1}$$

I_{mp} is the maximum power point current; V_{mp}, the maximum power point voltage and A_c, the area of the photovoltaic module.

According to Duffie and Beckman [3], the efficiency of the photovoltaic system at maximum power (η_{mp}) can be calculated through equation (2)

$$\eta_{mp} = \eta_{mp,ref} + \mu_{\eta,mp}(T_c - T_{ref}) \tag{2}$$

where T_c is the temperature of the cell substrata; T_{ref} the temperature of the cell at the standard reporting condition (SRC); i.e.: at $T_{ref} = 25$ °C and $G_T = 1000$ W/m^2, determined in compliance with recommendations of the American society for testing and materials (ASTM) [4].

Derivative of equation (2) with respect to the cell temperature yields the temperature coefficient:

$$\frac{d\eta_{mp}}{dT} = \frac{1}{A_c\,G_T}\left[\frac{dI_{mp}}{dT}V_{mp} + I_{mp}\frac{dV_{mp}}{dT}\right]. \tag{3}$$

For many modules, Duffie and Beckman [3] correctly observe that $\frac{dI_{mp}}{dT} \approx 0$ and $\frac{dV_{mp}}{dT} \approx \frac{dV_{oc}}{dT}$. Further manipulation of equation (3) at the maximum power point voltage (V_{mp}) yields the following expression for the calculation of the temperature coefficient of maximum power efficiency:

$$\mu_{mp} = \frac{d\eta_{mp}}{dT} = \eta_{mp}\frac{\mu_{V,oc}}{V_{mp}}. \tag{4}$$

Therefore, the maximum energy that results from the photovoltaic conversion is given by:

$$E_{mp} = \eta_{\eta,mp}\,A_c\,G_T. \tag{5}$$

3 Incident radiation at different geographic coordinates

Calculations of the cell temperature (required to calculate the efficiency of the photovoltaic and the energy obtained from this process) were repeated for the radiation conditions of eleven Brazilian cities located at different geographical coordinates, carefully selected to ensure favourable conditions for photovoltaic conversion and a broad range (longitude and latitude) of incident solar radiation. Table 1 summarizes the geographic coordinates and the meteorological data used in the selection of the cities participating in the study [5,6].

Duffie and Beckman [3] show that for a local latitude φ and a solar declination δ, the number of hours of light for each month of the year may conveniently be calculated by equation (6), whose results are presented in Table 2:

$$N = \frac{2}{15}\cos^{-1}(-\tan\varphi\tan\delta). \tag{6}$$

For the local conditions of each city studied, the total amount of incident solar energy (Wh) is determined by multiplying the daily average of solar radiation given in Table 1 by the total number of hours of sunlight given in Table 2.

4 Materials and methods

4.1 The photovoltaic array

Table 3 summarizes the technical characteristics (manufacturer's data) of the commercialized photovoltaic technology used in this study [7].

The cell temperature is a key parameter in modelling the performance and efficiency of photovoltaic conversion. In previous work developed by the same authors [2,8], the performance of three classical methods (Duffie and Beckman [3], King et al. [9] and Masters [10]) was compared among each other to assess their capability to calculate (based on official hourly meteorological data) the temperature $\overline{T_C}$ of cell.

4.2 Comparison between performance models

The three models establish expressions to determine the temperature of the cell, a critical parameter needed to calculate the photovoltaic conversion efficiency and, subsequently, the energy generated at standard steady state conditions [4]. The specific equation proposed for each one of the three performance methods considered is given below.

Table 1. Location of the selected cities and corresponding solar radiation.

City	State	*Geographic coordinates of the cities			**Ambient temperature	**Solar radiation
		Latitude (°)	Longitude (°)	Height (m)	(°C)	kwh/(m^2 dia)
João Pessoa	PB	−7.17	−34.83	47	26.1	5.50
Natal	RN	−5.83	−35.20	65	26.5	5.58
Fortaleza	CE	−3.80	−38.53	41	26.6	5.56
Recife	PE	−8,05	−34,95	10	27.5	5.89
Salvador	BA	−13.01	−38,51	51	24.8	5.27
Brasilia	DF	−15.79	−47.93	1.159	22.1	4.92
Belo Horizonte	MG	−19.88	−43.97	869	20.6	4.34
Vitória	ES	−20.32	−40.32	9	25.0	4.51
Rio Janeiro	RJ	−22,99	−43,19	45	24.3	4.64
São Paulo	SP	−23.50	−46,62	792	20.0	3.96
Manaus	AM	−3.13	−59.95	67	27.2	4.61

*Source: INMET (2013) [5]; ** RETSCREEN Int'l (2013) [6].

Table 2. Total monthly hours of incident radiation in the selected Brazilian cities.

Selected City	Month (2013)	$N = \Sigma$ (hours) of light	City	Month (2013)	$N = \Sigma$ (hours) of light
João Pessoa (PB)	January	383	Natal (RN)	January	381
	February	342		February	341
	March	373		March	373
Fortaleza (CE)	January	378	Recife (PE)	January	384
	February	339		February	363
	March	372		March	373
Salvador (BA)	January	392	Brasília DF	January	397
	February	347		February	349
	March	374		March	374
Belo Horizonte (MG)	January	404	Vitória (ES)	January	405
	February	353		February	354
	March	375		March	375
Rio de Janeiro (RJ)	January	410	São Paulo (SP)	January	411
	February	356		February	357
	March	376		March	376
Manaus (AM)	January	376	δ: solar declination, n: day of the year ($1 \leqslant n \leqslant 365$)		
	February	338	$\delta\,(\text{Jan}) = -20.9$ $\quad \delta\,(\text{Feb}) = -13.0$ $\quad \delta\,(\text{Mar}) = -2.4$		
	March	372	$\delta(\text{degees}) = 23.45 \sin[360(284 + n)/365]$		

Table 3. Technical data of the photovoltaic panel used (Q-Cells Technology [7]).

Technical characteristics of the photovoltaic technology used in the study [Manufacturer : Q-Cells]			
Model of the panne	QC-0O5-240	Temperature Coefficient at max power (μP mp)	−1.0800 W/°C
Conversion area	1.67 m^2	Temperature Coef. at max efficiency ($\mu\eta$ mp)	−0.000647/°C
Maximum power (Pmp)	240 W	Module temperature at NOCT condition	45.4/°C

$T_{ref} = 25$ °C; $C_T = 1000 \frac{W}{m^2}$ [5].

Table 4. Calculation of the cell temperature T_c from all three models studied.

City	January (2013) Cell temperature (K)			February (2013) Cell temperature (K)			March (2013) Cell temperature (K)		
	King et al.	Duff and Beck	Masters	King et al.	Duff and Beck	Masters	King et al.	Duff and Beck	Masters
João Pessoa	306.4	309.9	318.3	306.3	309.8	318.8	307.3	310.9	319.6
Natal	304.2	307.2	318.1	304.1	306.9	318.6	304.4	307.2	318.0
Fortaleza	306.0	309.0	316.6	305.8	308.6	316.7	306.5	309.4	316.6
Recife	306.2	309.3	316.1	306.0	309.1	316.5	306.6	309.7	316.1
Salvador	307.8	311.1	317.2	310.2	314.4	320.8	310.6	314.7	320.7
Brasilia	299.0	301.4	306.8	302.3	305.5	313.4	301.0	303.8	309.9
Belo Horizonte	302.0	304.6	309.1	304.4	307.9	315.4	302.8	305.6	311.2
Vitória	305.5	308.6	316.3	306.6	310.1	318.7	305.3	308.1	313.7
Rio Janeiro	302.6	305.1	311.3	305.9	309.4	316.9	303.3	305.8	311.8
São Paulo	299.1	301.2	305.0	303.8	307.1	311.5	300.7	303.2	307.9
Manaus	307.1	309.9	314.0	305.9	308.6	312.2	305.6	308.0	311.8

4.2.1 Cell temperature from Duffie and Beckman model [3]

$$\frac{T_c - T_a}{T_{NOCT} - T_{a,NOCT}} = \frac{G_T}{G_{T,NOCT}} \frac{9.5}{(5.7 + 3.8V)} \left(1 - \frac{n_c}{0.9}\right) \tag{7}$$

T_a is the ambient temperature; T_{NOCT} the temperature of the array at NOCT conditions (value provided by the manufacturer); $T_{a,NOCT}$ the ambient temperature (20 °C) at NOCT conditions; G_T the incident solar radiation; $G_{T,NOCT}$ the solar radiation (800 W/m^2) at NOCT conditions; V the wind speed at the location where the panel is installed and η_c the photovoltaic conversion efficiency at maximum power.

4.2.2 Cell temperature from King et al. model [9]

$$T_c = \left[G_T \left\{e^{a+b\,V}\right\} + T_a\right] + \frac{G_T}{G_{ref}} \mathit{\Delta} T \tag{8}$$

G_T is the incident solar radiation; a, the maximum acceptable limit for the temperature of the photovoltaic module for a low wind speed and high solar radiation level; b,a parameter that indicates the drop in cell temperature as the wind speed increases; V, the wind speed at the location of the PV panel; T_a the ambient temperature; G_{ref} the reference solar radiation of the PV module (1000 W/m^2); $\mathit{\Delta} T$, the temperature difference across the cell width for a level of radiation of 1000 W/m^2.

4.2.3 Cell temperature from Masters' model [10]

$$T_c = T_a + \left(\frac{T_{NOCT} - T_{a,NOCT}}{G_{T,NOCT}}\right) G_T \tag{9}$$

T_{NOCT} is the module temperature at NOCT conditions; i.e.: $T_a = 20$ °C; incident solar radiation of $G_T = 800$ W/m^2; wind speed of 1 m/s, in absence of any external loads ($\eta_c = 0$) [2].

All three models selected for this study have been extensively quoted in the literature but, to the authors' best knowledge, no one was validated as much as the model of King et al. Boyd [11] reports that, depending on the conditions of the experiments, the model of King et al. reproduces experimental data within 2.4% to 5.4%.

Based on a comprehensive set of independent calculations that takes into account technical characteristics of the photovoltaic array studied, the three models were used to calculate the substrata temperature of the photovoltaic cell (T_c) from the input data (solar radiation, wind speed and ambient temperature) associated with each one of the eleven selected cities. Data refers to the period of maximum radiation; i.e.: January to March. Calculations of cell temperature were then carried out based on the three selected performance models (i.e.: Eqs. (6)–(8)).

5 Results and discussion

5.1 Hourly average solar resource data

Table 4 summarizes the results of the calculations performed to obtain the temperature of the photovoltaic array through the performance models of Duffie and Beckman [3], King et al. [9] and Masters [10].

Calculated data (shown in Tab. 4) confirm that among the three models studied, the Model of King et al. is the one that systematically predicts the lowest cell temperature. As known, the lower the temperature of the cell exposed to an incident solar radiation, the greater its capacity to convert solar radiation into electricity. In short, less energy is lost to the environment.

Overall, average values calculated from data given in Table 4 confirms that, the model of Duffie and Beckman reproduced the calculation of the cell temperature obtained through the model of King et al. within 3 °C while the model of Masters exceeds the range of accuracy (cell temperature diverged 10 °C) of the King's model.

From the calculated cell temperatures (displayed in Tab. 4), equations (1) and (5) are used to calculate the photovoltaic efficiency and the energy generated from the photovoltaic conversion, respectively. Table 5 summarizes the results obtained based on official [5] hourly average solar resource data processed.

Among the studied models, King et al. systematically predicts higher values of the photovoltaic energy

Table 5. Photovoltaic efficiency and energy generated from the PV conversion.

City	January (2013)						February (2013)						March (2013)					
	King et al.		Duff and Beck		Masters		King et al.		Duff and Beck		Masters		King et al.		Duff and Beck		Masters	
	Effic (η, %)	Energy (kWh)	Effic (η, %)	Energy (kWh)	Effic (η, %)	Energy (kWh)	Effic (η, %)	Energy (kWh)	Effic (η, %)	Energy (kWh)	Effic (η, %)	Energy (kWh)	Effic (η, %)	Energy (kWh)	Effic (η, %)	Energy (kWh)	Effic (η, %)	Energy (kWh)
João Pessoa	13.8	48.28	13.6	47.13	13.1	44.33	13.8	43.48	13.6	42.42	13.0	39.65	13.8	48.34	13.5	47.04	13.0	44.05
Natal	14.0	49.08	13.8	48.10	13.1	44.51	14.0	45.32	13.8	44.46	13.0	40.84	14.0	46.96	13.8	46.03	13.1	42.50
Fortaleza	13.9	41.20	13.7	40.10	13.2	38.03	13.9	37.43	13.7	36.65	13.2	34.59	13.8	39.79	13.6	38.84	13.2	37.04
Recife	13.9	41.60	13.7	40.70	13.2	38.67	13.9	37.45	13.7	36.67	13.2	34.72	13.8	38.81	13.6	38.88	13.2	36.91
Salvador	13.8	44.90	13.5	43.77	13.1	41.64	13.6	47.40	13.3	45.82	12.9	43.75	13.6	50.25	13.3	48.74	12.9	46.76
Brasilia	14.3	34.50	14.2	33.83	13.8	32.34	14.1	41.19	13.9	40.19	13.4	37.79	14.2	37.98	14.0	37.09	13.6	35.27
Belo Horizonte	14.1	37.90	14.0	37.00	13.7	35.67	14.0	45.22	13.7	44.01	13.3	41.60	14.1	37.46	13.9	36.59	13.5	35.03
Vitória	13.9	47.10	13.7	45.88	13.2	42.87	13.8	46.02	13.6	44.92	13.0	42.17	13.9	37.03	13.7	36.12	13.4	34.41
Rio Janeiro	14.1	48.30	13.9	47.16	13.5	44.88	13.9	50.17	13.6	48.69	13.2	45.73	14.0	41.46	13.9	40.54	13.5	38.49
São Paulo	14.3	28.00	14.2	27.33	13.9	26.38	14.0	36.60	13.8	35.27	13.5	33.92	14.2	32.63	14.0	31.95	13.7	30.64
Manaus	13.8	36.00	13.6	34.96	13.3	33.65	13.9	30.94	13.7	30.00	13.5	29.01	13.9	29.39	13.7	28.67	13.5	27.72

Table 6. Comparison among the three performance models.

City	Differences (%) among the energy converted (with respect the King's Model)					
	January (2013)		February (2013)		March (2013)	
	E (king)− E (Duffie)	E (king)− E (Masters)	E (king)− E (Duffie)	E (king)− E (Masters)	E (king)- E (Duffie)	E (king)- E (Masters)
João Pessoa	2.4%	8.2%	2.4%	8.8%	2.7%	8.9%
Natal	2.0%	9.3%	1.9%	9.9%	2.0%	9.5%
Fortaleza	2.7%	7.7%	2.1%	7.6%	2.4%	6.9%
Recife	2.2%	7.0%	2.1%	7.3%	−0.2%	4.9%
Salvador	2.5%	7.3%	3.3%	7.7%	3.0%	6.9%
Brasilia	1.9%	6.3%	2.4%	8.3%	2.3%	7.1%
Belo Horizonte	2.4%	5.9%	2.7%	8.0%	2.3%	6.5%
Vitória	2.6%	9.0%	2.4%	8.4%	2.5%	7.1%
Rio Janeiro	2.4%	7.1%	2.9%	8.8%	2.2%	7.2%
São Paulo	2.4%	5.8%	3.6%	7.3%	2.1%	6.1%
Manaus	2.9%	6.5%	3.0%	6.2%	2.4%	5.7%

Table 7. PV array temperature: comparison among hourly- and monthly-data.

Selected City	January (2013) Cell temperature (K) Calculated from King et al.			February (2013) Cell temperature (K) Calculated from King et al.			March (2013) Cell temperature (K) Calculated from King et al.		
	Hourly	Monthly	ΔT (K)	Hourly	Monthly	ΔT (K)	Hourly	Monthly	ΔT (K)
João Pessoa	306.36	306.69	0.31	306.32	306.56	0.24	307.27	307.42	0.15
Natal	304.20	304.22	0.02	304.06	304.08	0.02	304.38	304.39	0.01
Fortaleza	306.01	305.38	0.63	305.75	305.44	0.31	306.50	305.88	0.62
Recife	306.19	306.62	0.43	306.01	306.40	0.39	306.64	307.02	0.38
Salvador	307.78	308.15	0.37	310.23	310.12	0.11	310.64	310.36	0.28
Brasilia	299.05	298.80	0.25	302.31	302.32	0.01	301.03	300.79	0.24
Belo Horizonte	302.00	301.77	0.23	304.39	303.86	0.53	302.79	302.39	0.40
Vitória	305.45	305.71	0.26	306.57	306.82	0.25	305.34	305.49	0.15
Rio Janeiro	302.62	301.74	0.88	305.88	305.21	0.67	303.27	302.23	1.04
São Paulo	299.13	298.76	0.37	303.76	301.48	2.28	300.73	300.18	0.55
Manaus	307.11	307.03	0.08	305.90	305.74	0.16	305.58	305.78	0.20
Average			0.3		0.5			0.4	

that results from the photovoltaic conversion, followed by the Duffie and Beckman which, in turn, produces results superior to those calculated by the model of Masters.

Even though the results of Table 5 may seem equivalent when visually compared, further calculations giving in Table 6 emphasizes the differences.

Based on hourly average solar resource data, results shown in Table 6 reveal that the model of King et al. [9] (taken as reference), systematically produces higher values of the energy converted, when compared with those calculated with the models of Duffie et al. [3] and Masters [10].

In average, when hourly average solar resource data are used, the amount of energy calculated by the model King et al is about 2.7% higher than that predicted by the model of Duffie and 8.7% higher than the predictions obtained with the model of Masters.

5.2 Monthly average solar resource data

Comparison of the three PV-conversion models elected the model of King et al.'s as the model to be used to evaluate whether or not monthly average solar resource data could replace hourly average solar resource data for predicting the efficiency of PV conversion and the amount of energy converted. The reason for the choice is twofold: King et al.'s model was validated against experimental data (2.4% to 5.4%, according to [11]) and it proved to reproduce Duffie et al.'s prediction within the accuracy of the method. Hence King's model was preferred to be used in the second part of the study; i.e.: recalculations of the PV efficiency and amount of energy converted when average monthly-based data is considered.

The temperature of the photovoltaic array was recalculated based on the monthly-based data and the new values are confronted in Table 7 with the correspondent hourly-based data previously calculated.

As can be observed, the agreement is outstanding, always better than 1 K (=1 °C), agreement even better (0.5 °C) when data are smooth out by the 3-month average processing taking into account the radiation conditions associated with all eleven cities.

Taking into account the new values of the cell temperature calculated through the average monthly-based data, Table 8 summarizes the results obtained for the new calculation of the PV efficiency of conversion and of the amount of energy converted.

Table 8. PV efficiency and energy converted based on hourly-based data.

Selected city	Photovoltaic conversion in January (2013)						Photovoltaic conversion in February (2013)						Photovoltaic conversion in March (2013)					
	Efficiency (η, %)		Energy (kWh)		($\Delta\eta$)	$\Delta(E)$/ Ehr	Efficiency (η, %)		Energy (kWh)		($\Delta\eta$)	$\Delta(E)$/ Ehr	Efficiency (η, %)		Energy (kWh)		($\Delta\eta$)	$\Delta(E)$/ Ehr
	(Hourly)	Monthly	Σ (Hourly)	Monthly			(Hourly)	Monthly	Σ (Hourly)	Monthly			(Hourly)	Monthly	Σ (Hourly)	Monthly		
João Pessoa	13.84	13.82	48.28	46.00	0.02	5.0%	13.84	13.83	43.48	41.27	0.02	5.4%	13.78	13.77	48.34	46.33	0.01	4.3%
Natal	13.98	13.98	49.08	46.22	0.00	6.2%	13.99	13.99	45.32	42.09	0.00	7.7%	13.97	13.97	46.96	44.06	0.00	6.6%
Fortaleza	13.86	13.90	41.20	39.75	−0.04	3.6%	13.88	13.90	37.43	35.48	−0.02	5.5%	13.83	13.87	39.79	38.28	−0.04	3.9%
Recife	13.85	13.82	41.59	40.20	0.03	3.5%	13.86	13.84	37.45	35.69	0.02	4.9%	13.82	13.80	39.81	38.15	0.02	4.3%
Salvador	13.75	13.72	44.91	43.67	0.02	2.8%	13.59	13.60	47.40	45.98	−0.01	3.1%	13.56	13.58	50.25	49.01	−0.02	2.5%
Brasilia	14.31	14.33	34.48	33.59	−0.02	2.7%	14.10	14.10	41.19	40.08	0.00	2.8%	14.18	14.20	37.98	36.4	−0.02	4.3%
Belo Horiz	14.12	14.14	37.91	36.04	−0.02	5.2%	13.97	14.00	45.22	42.96	−0.03	5.2%	14.07	14.10	37.46	36.93	−0.03	1.4%
Vitória	13.90	13.88	47.12	44.80	0.02	5.2%	13.83	13.81	46.02	43.37	0.02	6.1%	13.91	13.90	37.03	35.34	0.01	4.8%
Rio Janeiro	14.08	14.14	48.30	38.43	−0.06	25.7%	13.87	13.91	50.17	43.43	−0.04	15.5%	14.04	14.11	41.46	35.43	−0.07	17.0%
São Paulo	14.31	14.33	28.00	29.27	−0.02	−4.3%	14.01	14.15	36.60	37.64	−0.15	−2.8%	14.20	14.24	32.63	32.46	−0.04	0.5%
Manaus	13.79	13.80	35.99	34.46	−0.01	4.4%	13.87	13.88	30.94	29.46	−0.01	5.0%	13.89	13.88	29.39	30.07	0.01	−2.2%
Average (%) (hr-based)						5.4%						5.3%						4.3%

6 Conclusion

As shown, if a level of tolerance of 5.4% is acceptable, the monthly average solar resource data can be used to calculate the energy generated from the photovoltaic conversion when hourly average solar resource data are not available.

From the economic point of view, the use of monthly average solar resource data drastically reduces costs associated with digital processing of massive data bases while reducing higher uncertainty associated with recurrent hourly average solar resource data of low quality.

This work contributes to an ongoing debate over the widespread use of photovoltaic energy – an attractive renewable energy source – in Brazil to diversify its energy matrix [2,8,12].

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