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Solar Enegy Resource in Madeira Islands (Portugal): Maps and Daily Evolution of Global Solar Radiation

Izquierdo P.[1], Vazquez V.[1], Santos JM.[1], Magro C.[2]

1. Mechanical Engineering Dpt., University of Vigo, Lagoas-Marcosende, 36310, Vigo, Spain.

2. Regional Laboratory of Civil Engineering, Govern of Madeira, Rua Agostino, 9000-264, Funchal, Portugal.

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Abstract: In this paper, solar energy resource study in madeira islands (portugal) is realized. In a first approach, solar irradiances at ground level are obtained applying the heliosat-2 method to earth images taken by the meteosat-6 satellite. these results are, in turn, calibrated (normalized) with data of solar radiation measured in six meteorological stations in the region. also, daily evolution of horizontal global solar radiation and temperature are characterized in these six stations, which depicted the different climatic areas of the archipelago.

Twelve monthly tables of daily average global solar radiation in each pixel of the image included in the study are obtained and yearly values are calculated from them. the thirteen tables are taken to the arcgis application to obtain yearly and monthly radiation maps for the region.

Also, monthly and yearly characteristics days of the region, six representative stations data base are study. in relation to solar radiation, characteristic day is defined as the day of the month with the sun trajectory closest to the daily average sun trajectory of the month and the daily global horizontal solar irradiation equal to the daily average of the month. it is assumed a sine-type evolution of the global irradiances along the day. in relation to temperature, a characteristic day is also assumed to have a sine-type evolution along the daylight hours of the day, with the minimum and maximum values at sunrise and two hours after noon, respectively.

Key words: solar energy irradiation, characteristic day, radiation maps, Madeira Archipelago

1. Introduction

The aim of this paper is to obtain the Solar Atlas of the Madeira Archipelago (Portugal). Also, monthly characteristic days are determined in six representative climatic areas in the Archipelago, due to the knowledge

Corresponding author: Izquierdo P., Mechanical Engineering Dpt., University of Vigo, Lagoas-Marcosende, 36310, Vigo, Spain.

of short-term (from minute to hourly) values of solar radiation and temperature, for an extended period of time, is necessary for the estimation of the solar photovoltaic energy potential. In case only daily values are available (daily solar radiation and average, maximum, and minimum temperatures), a good approach is to try to characterize the daily evolution of those variables from the daily values.

The Archipelago is in the Atlantic Ocean and is formed by the main island of Madeira (roughly 57 km long E-W and 23 km wide N-S), Porto Santo Island (12 km E-W, 7 km N-S), and the small uninhabited Desertas Islands closed to the main island.

In regions where the number of radiometric stations is scarce to characterize the climatic diversity of the region, it has been common for the last years to use images of the earth taken by meteorological satellites in the visible range of the solar spectrum to estimate the available solar radiation and to elaborate atlas of solar radiation for the regions (1, 2). That happens in the Madeira island where altitudes vary from 0 to near 1.900 m in small distances causing the weather to change abruptly not only in altitude but also as a function of the geographical position (North or South), In those cases, the maps obtained have more accuracy than maps elaborated from only database of meteorological stations, as it has been shown in other papers (3).

In relation to the characteristic climatic (radiation and temperature) day, there are several works that stablished a methodology to define a representative day for each month. In relation to solar radiation, there are works (4, 5) dealing with the determination of hourly radiation values from daily values, and also parameterizations of irradiance (6). In relation to temperature, there are also works that estimate daily evolution of temperature from registered daily maximum and minimum values (7, 8). In this work, we have followed this approach and considered sine-type daily evolutions of solar irradiance and ambient temperature, in order to accomplish a study of the estimation of the solar photovoltaic energy potential in six defined climatic areas of the Madeira Archipelago. The areas are represented by the variables recorded in six corresponding stations.

In the present work we used the images taken by the European geostationary satellite Meteosat-6 in the period 2002-2005, and supplied by the Eumetsat organization (9). In this period, the satellite was in the Rapid Scan Service and sent every ten minutes an image covering the area of North Africa, Europe, Middle East and the Atlantic Ocean. Only the subsection of the images containing the Madeira archipelago was used in the computes. The Heliosat-2 (10) method was applied to the subsections that let to obtain irradiances and, by integration, irradiations. These values were, in turn, calibrated (normalized) with solar radiation data measured in six meteorological stations in the region, and the monthly and yearly maps of daily average global solar radiation were obtained.

Data Base

The Meteosat-6 satellite was located over the Equator at 0º Longitude from January 2002 till April 2003 and from that month till December 2005 at 10º East Longitude. Satellite images are composed by pixels that just below the satellite in the Equator, correspond to geographical places 2.5 km apart from each other. The pixels are identified by the row number (known as line number) and the column number (known as pixel number). The information in the image gives a value from 0 to 255 (in a gray scale) of each pixel. That number is related with the cloudiness over the site corresponding to the pixel in the instant the image was taken.

The Meteosat-6 satellite in the Rapid Scan Service took one image (known as scan) every ten minutes and sent a bundle of three images (known as slot) every half an hour. So, till 144 images a day could be available but not all those images were necessary for this work. Night time images are useless. On the other hand, it was shown in a previous paper (11) that the images of five slots (total of 15 images) well distributed along the day could be enough to estimate the global irradiation of the day. Therefore, we used here the images of the slots numbers 16, 20, 24, 28 and 32 that correspond to the images of the half-hours previous to the UTC hours 8:00, 10:00, 12:00, 14:00 and 16:00 for each day of the four-year period 2002-2005.

The images were cut out to a number of 41 lines and 66 pixels, totaling 2.706 pixels, more or less coinciding with the area between 32º15’- 33º15’ North Latitude, and 16º15’- 17º30’ West Longitude, that covers the hole archipelago of Madeira.

The application of the Heliosat-2 method requires as input parameters the Linke turbidity factor for an air mass of 2 and the elevation of the site. The Linke turbidity factor data base was obtained from the Institute for Environment and Sustainability (IES) (12). The elevation of the site was obtained from the Global Land One-km Base Elevation (GLOBE) database (13). The elevation of each pixel of the image was calculated averaging the elevations of the points in the Globe database included in its coverage area.

For the normalization (calibration) of the irradiations obtained from the Heliosat-2 method we used the daily irradiations measured in six stations owned by the Meteorological Institute of Portugal in the Autonomous Region of Madeira. From these stations, not only daily horizontal global solar irradiations are used to calibration of the maps, but also for defined the characteristics days of the six representative climatic areas in the Archipelago. Also, daily maximum and minimum temperatures of the same period were used (January 2002- December 2005).

Stations geographic coordinates are shown in Table 1 (the fourth column is the altitude in meters above sea level). The Porto Santo station is in the island of the same name and, given the small size of the island, the station can characterize it. The rest of the stations are in the main island of Madeira. Areeiro station is located in the mountainous interior part of the island and characterizes that area. The other four stations are in the cost. Funchal and Lugar de Baixo to the South, Ponta do Pargo to the West, and São Jorge to the North.

Other geographical data, such as geographic limits of different councils, the localization of main cities and towns and significant mountain peaks in the Madeira Archipelago, needed for the generation of the maps by means of their implementation in the ArcGIS software, were obtained from the Institute of Environment of Portugal. (14).

Table 1: Madeira archipelago meteo-stations geographic coordinates

Station	*Latitude (North)*	*Longitude (West)*	*Meters above sea level (a.s.l)*
Areeiro	32º 43' 15"	16º 54' 49"	1510
Funchal	32º 38' 46"	16º 53' 27"	58
Lugar de Baixo	32º 40' 47"	17º 05' 28"	48
Ponta do Pargo	32º 48' 44"	16º 53' 27"	312
São Jorge	32º 49' 54"	16º 54' 24"	271
Porto Santo	33º 04' 23"	16º 20' 50"	82

2. Methodology

Application of the Heliosat-2 Method to the Images of the Satellite and Normalization

The Heliosat-2 program libraries were obtained from a previous study of l'Écôle des Mines de Paris (1), and implemented in C++ language programs that we had arranged for a previous work (15). The application of the method to the images let estimate horizontal solar global irradiances in the sites corresponding to the pixels of the image for the instants that the images were taken. Integration of the fifteen available values per day let obtain daily irradiations for the four-year period analyzed. From them, monthly average daily global irradiations are determined for all the pixels in the region. These results can be considered as an un-calibrated (or un-normalized) first approach.

Normalization or calibration consist on the correction of the values obtained by the Heliosat-2 method, which was applied to the satellite images, with solar radiation data measured in meteorological stations in the region. Goodness of this procedure was study in a previous paper, for another region (16). The proceeding consists on assigning the recorded data in the station to the pixel closest to the station, on obtaining a coefficient by dividing that recorded value by the un-normalized value in that pixel, and then on multiplying the un-calibrated values of the pixels of similar climatology in its neighborhood by the coefficient, to obtain the absolute values.

In this case, stations are fairly well situated to characterize the diversified geo-climatic characteristics of the Madeira archipelago. The zones in which the archipelago was divided are shown in next figure (Fig. 1).

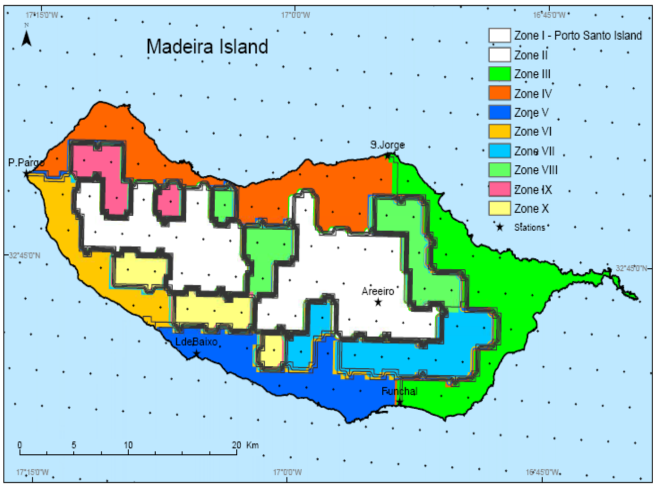

Fig. 1: Geographical zones of the Madeira Archipelago

The Porto Santo Island was normalized with its own station (zone I, not shown in the figure).

In the Madeira Island, the Areeiro station in the high altitudes in the interior of the island was used to normalize that part of similar climatology (zone II). The four stations of Funchal, Lugar de Baixo, Ponta do Pargo and São Jorge are situated beside the coast around the island what let divide all the coast around in four zones each limited by its neighbor pair of stations. These were used for the normalization by weighting their values in the interpolation as a function of the inverse of the quadratic distance (zones III to VI). The rest of the zones of the Madeira Island that could not be clearly attributed to one of the just mentioned were normalized by interpolating with the normalized values of their neighboring zones (zones VII to X). The Desertas islands and the pixels on the sea were normalized by interpolation from their closest normalized zones in the Madeira and Porto Santo Islands.

Radiation Maps

After the normalization procedure, twelve monthly data base of average daily solar global irradiations were obtained for the pixels in the region and, from them, the yearly data base. From the data, the twelve monthly average daily global solar irradiations and the yearly average daily global solar irradiations were calculated for the four-year period and the six stations, as it is show in Table 2.

Table 2: Monthly average daily global solar irradiation in the madeira stations (Wh/m^2 day)

Station Month	Areeiro	Funchal	LBaixo	PPargo	SJorge	PSanto
January	3146	2846	2775	2754	2392	2734
February	3194	3419	3474	3469	2982	3632
March	4495	4643	4628	4428	4041	5019
April	5130	4683	5044	5577	4893	6155
May	6637	5691	6144	6765	5553	7306
June	7470	5601	6136	7285	6175	7095
July	8023	5614	6024	7232	5770	7075
August	6402	5496	5960	6496	6016	6545
September	5232	5043	5217	5155	4891	5534
October	3790	3691	3879	3862	3617	4056
November	2517	2865	2922	2753	2339	3123
December	2305	2481	2568	2547	1972	2511
Year Average	4873	4345	4570	4868	4226	5073

These data base were taken to the ArcGIS geo-referencing software and the twelve monthly maps and the yearly map were obtained by means of the inverse distance weighting (IDW) technique. As example, yearly global radiation map is shows below (Fig. 2). According to these maps, that the monthly daily average horizontal global solar irradiation varies from a minimum of 2.00 kWh/m^2.day in December, in the North of the Madeira Island, to a maximum of 8.80 kWh/m^{2}day in July, in the interior of that island. On a yearly average, the minimum is found in the North of the Madeira Island with 4.00 kWh/m^{2}day, till a maximum of 5.00 kWh/m^2 day in the interior of that island and also in Porto Santo Island.

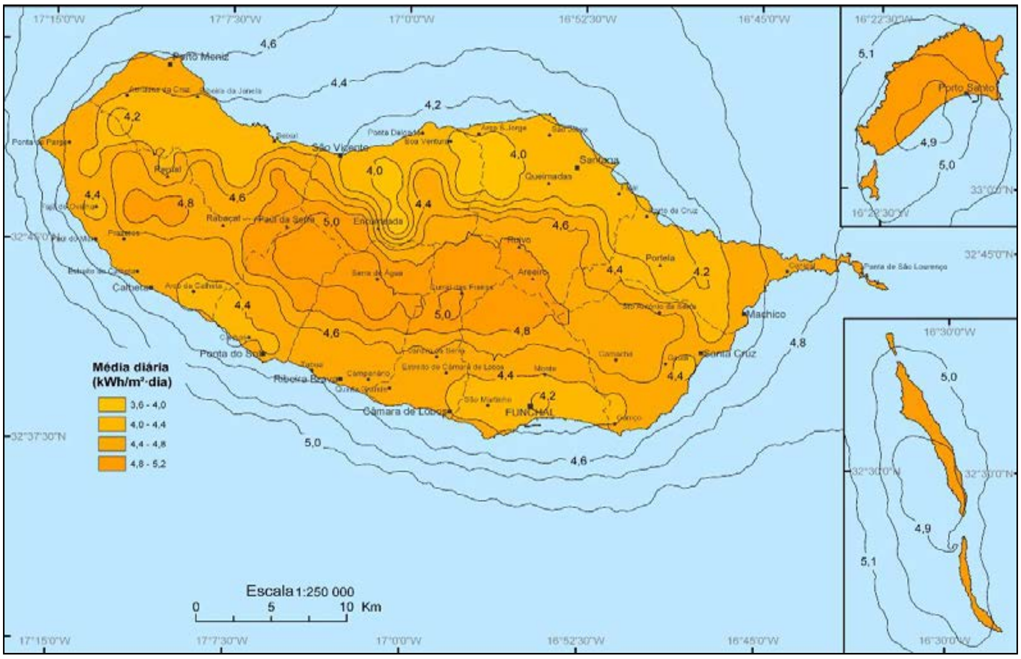

Fig. 2: Yearly map of daily average solar radiation of the Madeira Archipelago (Portugal)

Characteristic day: solar radiation and temperature

First step to the definition of the characteristic day is selecting one day of each month as representative of that month. In this study, according to literature (17), the twelve characteristics days were selected based on the Sun trajectory, which it's means that it was chosen the day in where Sun trajectory was the closest to the average Sun trajectory of all the days in the month. Table 3 shows those days and their Julian number.

Table 3: Characteristic day of each month

Month	*Month characteristic day (Julian day)*	*Month characteristic day (Month day)*
January	17	17
February	46	15
March	76	15
April	106	16
May	136	16
June	163	12
July	199	18
August	229	17
September	259	16
October	289	16
November	319	15
December	345	11

In relation to solar radiation, according to literature (6), a sine-type evolution of the solar irradiance along the day is assumed *(Eq. 1)*:

$$I = A \cdot \cos\left(\frac{\pi}{2} ? \frac{\omega}{\omega_s}\right) \text{, with } -\omega_s \leq \omega \leq \omega_s \qquad (Eq.\ 1)$$

In this equation, ω is the solar hour angle in radians and $-\omega_s$ and ω_s are the solar angles at sunrise and sunset, respectively. *A* is a number such that the integration of the *Eq. 1* along the characteristic day is equal to the value of the daily global radiation G_d in that day (month average). *A* can be obtained by *Eq. 2*

$$A = \frac{G_d \cdot \pi^2}{48 \cdot \omega_s} \qquad (Eq.\ 2)$$

Taking into account that ω is related to the solar time in minutes (min) as shown in *Eq. 3*

$$\omega = (\min - 720) \cdot \frac{15}{60} \cdot \frac{2\pi}{360} \qquad (Eq.\ 3)$$

And ω_s and $-\omega_s$ are obtained by *Eq. 4* according to literature (6) where *L* is the latitude of the site and δ is the declination of the Sun obtained with *Eq. 5* (*n* is the Julian day)

$$\omega_s = \pm \arccos(-\tan L \tan \delta) \qquad (Eq.\ 4)$$

$$\delta = 23{,}45 \cdot \left(\frac{2\pi}{360}\right) \cdot \sin\left(2\pi \cdot \frac{284 + n}{365.25}\right) \qquad (Eq.\ 5)$$

Because of the narrow margin of variation of latitudes in the archipelago (and so in the stations), an average latitude of 32º45' is used for all the stations in order to better compare the results. In next figure (Fig. 3) it is shown, as an example, the evolution of global solar irradiance (W/m^2) in the characteristic day of April in the six stations.

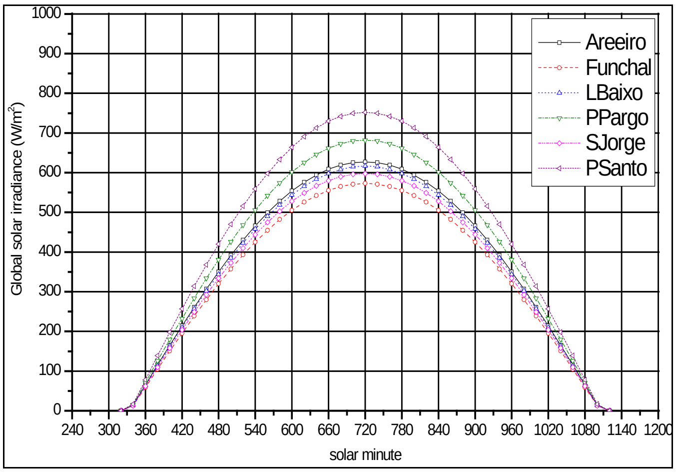

Fig 3: Global solar irradiance (W/m^2) day evolution in April for the six stations

In relation to temperature, the twelve monthly average and the yearly average daily maximum (T_M) and minimum (T_m) temperatures were calculated. The results obtained are shown in Table 4.

Table 3: Monthly average of range (minimum-maximum) day temperatures in the Madeira Stations (ºC)

Station Month	Areeiro	Funchal	LBaixo	PPargo	SJorge	PSanto
January	4.05-9.33	14.33-20.39	15.10-20.82	12.35-17.62	12.63-17.10	13.30-18.24
February	3.13-7.83	13.76-20.12	14.56-20.72	12.03-17.40	12.30-16.93	13.08-18.29
March	3.88-9.38	14.11-20.74	14.78-21.17	12.40-17.73	12.46-17.80	13.08-18.64
April	3.82-9.56	14.54-20.93	15.13-21.44	12.64-18.67	12.67-18.05	13.87-19.35
May	5.75-11.80	15.96-22.48	16.41-25.92	14.12-20.70	14.12-20.16	15.45-20.78
June	9.82-16.79	18.70-24.55	19.07-25.92	16.78-23.58	16.68-23.03	18.46-23.33
July	11.22-18.21	20.11-26.50	19.07-25.92	18.23-25.73	17.99-24.72	19.96-25.27
August	11.55-18.22	20.99-27.73	20.40-27.31	19.21-26.12	19.10-25.58	20.98-26.24
September	10.59-17.01	20.64-27.60	21.27-28.36	18.98-25.70	18.75-25.30	20.39-25.57
October	8.05-14.15	19.01-25.35	21.07-27.94	17.21-22.65	17.00-22.55	18.02-23.18
November	5.53-10.38	16.54-22.55	19.38-25.53	14.76-19.90	14.86-19.56	15.55-20.32
December	4.28-8.95	15.16-21.08	17.06-23.22	13.45-18.09	13.38-17.72	14.47-18.51
Year Aver.	6.83-12.66	17.01-23.36	17.53-23.95	15.20-21.18	15.18-20.73	16.40-21.50

It is assumed that the temperature T (ºC) varies, along the daylight time, following a sine function given by *Eq. 6* ,in which, according to literature (7), the maximum daily temperature is supposed to happen two hours after noon (daily minute 840), and the minimum daily temperature at sunrise.

$$T = T_m + (T_M - T_m) \cdot \sin\left(\frac{\pi}{2} \cdot \frac{\min - \min_0}{840 - \min_0}\right), \ \min_0 < \min < \min_f \qquad \textit{(Eq. 6)}$$

In this equation, the minute solar of the day (min) is chosen as independent variable and $\min_0$ is the solar minute at sunrise and $\min_f$ at sunset. Fig. 4 shows, as an example, the evolution of ambient temperature (ºC) in the characteristic day of April in the six stations.

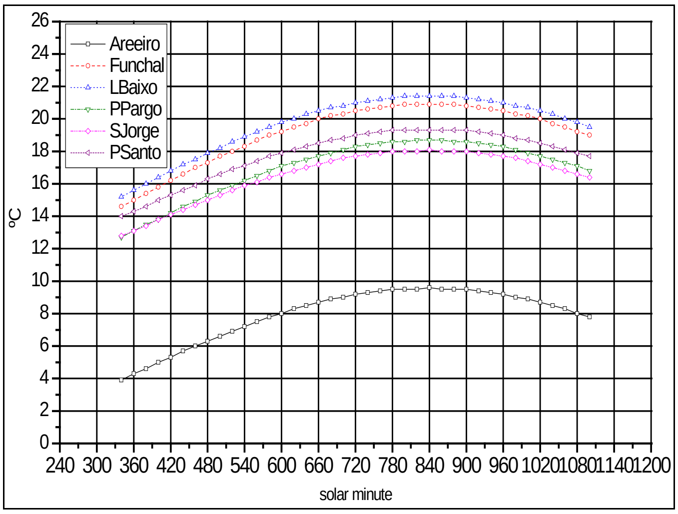

Fig 2: Temperature (ºC) day evolution in April for the six stations

3. Conclusions

This paper shows the proceeding used to obtain the maps of global solar radiation for the archipelago of Madeira. The data base used consists of images of the Meteosat-6 satellite for the period 2002-2005, and global solar radiation data of the six meteorological stations operated by the National Meteorological Institute of Portugal in Madeira for the same period. The Heliosat-2 method was applied to the images to obtain un-calibrated irradiations in the pixels of the images. These values were, in turn, calibrated with the data in the stations, for which the area was subdivided in zones of similar geo-climatology.

Twelve monthly and the yearly daily average global solar radiation maps were obtained for the region. The maps have shown that the average horizontal global solar irradiation varies from a minimum of 2.00 kWh/m2day in December in the North of the Madeira Island to a maximum of 8.80 kWh/m2day in July in the interior of that island. On a yearly average, the minimum is found in the North of the Madeira Island with 4.00 kWh/m2day, till a maximum of 5.00 kWh/m2day in the interior of that island and in Porto Santo as well.

Also, the daily evolution of horizontal global solar radiation and temperature in six climatic areas of the Madeira archipelago is obtained for the characteristic day of each month of the year, from a data base of daily horizontal global solar irradiations and daily maximum and minimum temperatures of a four-year period (January 2002-December 2005), of six stations owned by the Meteorological Institute of Portugal in the Autonomous Region of Madeira. Irradiance values along the day, estimated from the sine function applied to the measured daily data, were checked against hourly measured irradiation values in one of the stations, Funchal, showing a fairly good agreement. Nevertheless, it is important to remark that the sine distribution tends to underestimate the values of solar irradiance around the noon and to overestimate them around sunrise/sunset time.

From the data, the twelve monthly average daily global solar irradiations and the yearly average daily global solar irradiations were calculated for the four-year period and the six stations. Also were calculated for the same period and stations the twelve monthly average and the yearly average daily maximum and minimum temperatures:

In relation to solar radiation, a characteristic day is defined as the day of the month with the Sun trajectory closest to the daily average Sun trajectory of the month, and the daily global horizontal solar irradiation equal to the daily average of the month. It is assumed a sine-type evolution of the global irradiances along the day that, by integration, must equal the monthly daily average global irradiation.

In relation to temperature, a characteristic day is also assumed to have a sine-type evolution along the daylight hours of the day, with the minimum and maximum values at sunrise and two hours after noon, respectively. The characteristic minimum and maximum values are obtained averaging the daily minimum and maximum values of the month, respectively.

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