

ANALYSIS OF BRAZILIAN SOLAR IRRADIANCE DATA: CHARACTERISTIC CURVES OF EACH NATIONAL GRID'S SUBSYSTEM

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Overview

The growing energy demand, allied to the fact anthropic activities depend heavily on fossil fuels, has been altering the characteristics of the global climate systems. As new technologies appear it's paramount to understand their behaviour, benefits, applicability and limitations in order to best harness it's potential. This paper aims to characterize Brazil's solar radiation throughout the country, grouped by the subsystems used by the Brazilian electrical system operator (ONS). The data used consists of five years of hourly kJ/m^2 data from 26 cities spread throughout the country. The data is treated, screened for outliers using Grubb's method, analysed and presented in the form of curves. This data can help better understand the role solar energy can take in the country's supply.

Keywords – Solar radiation; solar power; renewable energy; photovoltaic generation; Grubbs test for outliers.

1. Introduction

One of the barriers standing in the way of renewable energy systems (RES) adoption is the absence of control over natural systems, in this case, weather (Reddy & Painuly, 2004). While a conventional thermal power plant can be turned on and off based on energy demand, or water can be stored in reservoirs as potential energy, sunlight and winds cannot be put on standby. Surely the energy produced by a photovoltaic power plant or a wind power plant can be stored in batteries, but the use of storage technologies can make these plants much more expensive and often economically unviable.

The challenges imposed by the unpredictability from said systems are being reduced as more research is conducted on the subject and more data emerges. With more robust prediction models, it's possible to develop policies to stimulate the adoption of RES whilst maintaining energy security (Langniß, Diekmann, & Lehr, 2009).

1.1. - Objectives

This paper aims to characterize Brazil's solar radiation in the subsystems used by the Brazilian electrical system operator (ONS) to manage load and generation. This subdivision is highly connected to weather types and hydrological basins, therefore having an important correlation with energy consumption and generation capabilities.

1.2. - Structure

The following sections will present first, in section 2, a literature review on solar energy, specifically the Brazilian scenario and photovoltaic (PV) distributed generation (DG). Then, in section 3, the used methodology will be described, in section 4, results and discussion, and in section 5 conclusions and recommendations for future work.

2. Literature Review

This section presents key aspects of solar radiation, solar energy scenario in Brazil and PV generation to contextualize this work and back up the methodology, results and conclusions.

2.1. - Harnessing Solar Radiation

From the total yearly solar energy that reaches the planet, with an average power of 1366 W/m^2 , only 0,01% would be enough to see to the planetary energy demand from 2005 to 2010. However, only a portion of about 12,5% reaches dryland surface, yet still, 0,1% of this energy would suffice to meet humanity's annual energy needs (Chen, 2011).

From an electricity generation standpoint, this resource can be harnessed in two ways, through PV or heliothermic conversion. The PV effect consists of directly converting sunlight into electric current whereas heliothermic power plants use solar concentrators to heat a special fluid which will then heat water producing vapour then used in a Rankine cycle to generate electrical energy (Chen, 2011; EPE, 2014).

2.2. - PV Scenario in Brazil

The Energy Research Company (EPE) conducts research to better understand the Brazilian energy grid in order to support energy expansion planning (EPE, 2009). The 10-year expansion plan for 2023 (EPE, 2014) addresses the expansion of RES separately. The plan foresees the insertion of large scale centralized PV plants in 2017 and further increasing the capacity from 25 MW to 664 MW by 2023 (EPE, 2014). The EPE also foresees that by 2023 PV systems will contribute with 877 GWh, a significant increase from the 37 GWh in 2014 (EPE, 2014). This plan is revisited yearly, the previous one estimates a larger insertion of PV energy in comparison to the 2023 plan, this was due to a change in taxation policy towards distributed generation, leading to a more conservative estimation (EPE, 2013; EPE, 2014).

2.3. - Distributed Photovoltaic Generation Characteristics

One of the greatest technical barriers opposing the adoptions of RES is the variability due to climate conditions, more specifically cloud transients (Reddy & Painuly, 2004). This variability can be reduced, according to Murata, Yamaguchi, & Otani (2009), if several plants are connected to the grid and sufficiently separated. As of 9 km separation, the high-frequency and high-intensity variations due to fast cloud transients is mitigated, increasing the reliability and energy quality from PV energy systems.

Besides renewable energy supply, PV systems can be combined with other clean solutions, such as electric vehicles. According to Nichols et al. (2015), the use of plug-in electric vehicles (PEVs) has a great positive impact in local air quality, however, if the primary energy source used to charge the vehicles isn't clean, the environmental impact will only have shifted locations.

However great the appeal for combining PEVs and PV distributed generation is, this ensemble has its technical and behavioural limitations. A simulation run by Munkhammar et al. (2015), modelling the problem in a residential scale, determined that generation would only be able to supply power for homes and PEV charging during peak hours. Due to both load demand and time schedule of vehicle charging, would end up increasing load on the power grid.

On the other hand, the simulation run by Tovilovic & Rajakovic (2015) considered an urban area with residential, commercial and industrial load profiles. The results presented that, in most of the analysed cases, the PV-PEV ensemble results in a reduction of baseline loads. In this scenario, load demand was slightly higher than with PV without PEVs.

Another concern regarding high penetration of distributed generators arises from voltage regulation and harmonic currents. One of the main causes of harmonics is the elevated amount of inverters from all the different generators (Liu et al., 2008; Guo et al., 2014).

3. Method

This section will describe methods and tools used to organise and analyse the used data.

3.1. - Solar Radiation Data

The data used in this paper consists of hourly insolation data in KJ/m^2 from the 25 state capitals plus the federal district. Data was supplied by the National Meteorology Institute (INMET). The series runs from 01/01/2009 to 31/12/2013, totalizing five years of data.

Season separation was done on the days of March 21st, June 21st, September 21st and December 21st, except for the first summer and last spring due to starting and finishing dates respectively. Besides the separation by seasons, the second subdivision is by the Unified National System (SIN), the country's power grid, each subsystem has its own energy generation and demand characteristics, as well as weather types.

3.2. - Data Processing and Analysis

First, the data was visually inspected to identify possible impairments to the data processing algorithms, such as missing data or invalid values. After this initial verification, a test was conducted to find statistical abnormalities in the measurements. An outlier is a value that lies outside the statistically acceptable bounds of the sample. An outlier is not necessarily an error, it may represent an important anomaly or event, however for the purpose of this paper, outliers were considered errors (Waal, Pannekoek, & Scholtus, 2011).

There are different tests to determine if a value is an outlier, due to its robustness and accuracy the Grubb's test was chosen (Lucato et al., 2007; Moreira et al., 2002; Oliveira, 2008). The Grubb's test can detect outliers in samples that follow an apparently Gaussian normal distribution (NIST/SEMATECH, 2013).

From the different methods for addressing missing data in a sample described by Allison (2001), single imputation was chosen to correct the data that was considered an outlier. The input value consisted in either the average

between the previous and next hour of the same day or, if those were considered outliers too, then the average between the same hour of the previous and next day was used.

4. Results and Discussion

The final result is presented in the form of twelve curves with the insolation profile for each of the four subsystems and the three representative seasons analysed. In this section, the curves are presented in graphs comparing the different seasons and subsystems. The graphs presented follow the same layout, the x-axis consists of hours of the day and the y-axis consists of insolation values in kJ/m^2 .

4.1.- Comparison by Subsystem

To better understand the behaviour of solar radiation in each subsystem throughout the year, this section presents the curves for each subsystem compiled into four graphs.

The insolation curves from the South subsystem, composed by the states of Paraná, Santa Catarina and Rio Grande do Sul (ANEEL, n.d.) displays the well-defined seasons present in temperate climates (Figure 1). From a PV generation standpoint, the South suffers from great variation in insolation throughout the year, reaching 30 – 40% between summer and winter.

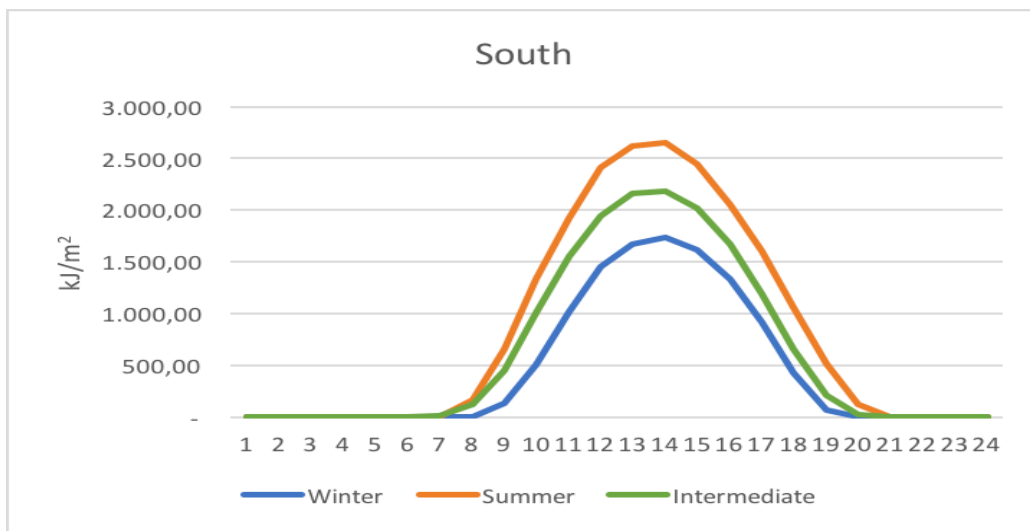


Figure 1 - Hourly insolation curves from the South subsystem for each season.

The Southeast/Midwest subsystem, composed by the states of Rio de Janeiro, São Paulo, Espírito Santo, Minas Gerais, Mato Grosso, Mato Grosso do Sul, Goiás, Distrito Federal, Acre e Rondônia (ANEEL, n.d.) shows low variability between seasons (Figure 2). The constant insolation throughout the year is a good indicator from a planning standpoint.

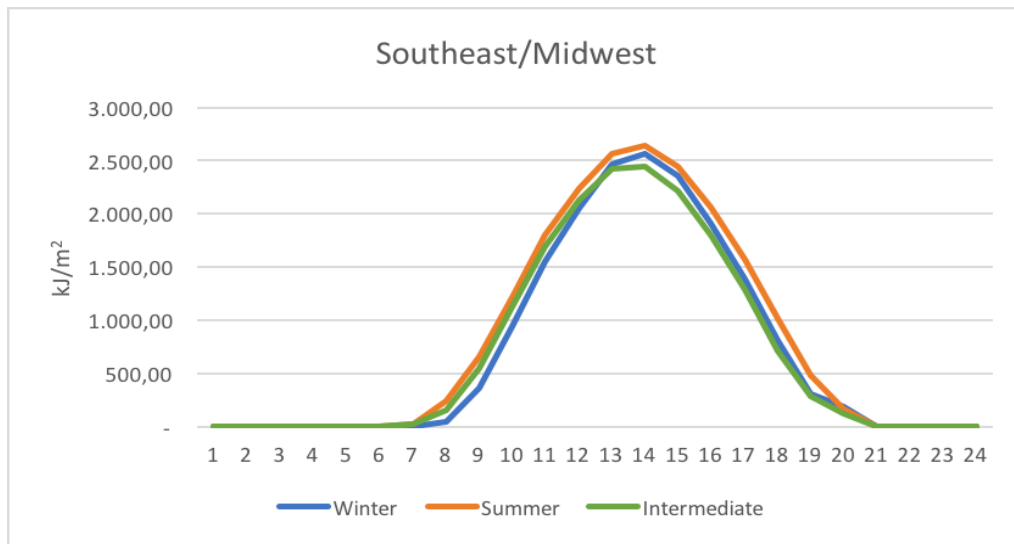


Figure 2 - Hourly insolation curves from the Southeast/Midwest subsystem for each season.

The reason for the lower variability isn't due to smaller variations of solar angle of incidence, but probably to weather patterns. In this subsystem, winter is the dry season, meaning more hours of insolation due to less rain. Humidity is also lower in the winter, causing less scattering of sunlight in the atmosphere before reaching the surface.

The Northeast subsystem, composed by the states of Rio Grande do Norte, Alagoas, Piauí, Sergipe, Ceará, Bahia, Pernambuco, and Paraíba (ANEEL, n.d.). The insolation in this subsystem varies more along the year than the Southeast/Midwest, however, the amount of insolation in the lowest season in Northeast is roughly the same as the highest in Southeast/Midwest (Figure 3).

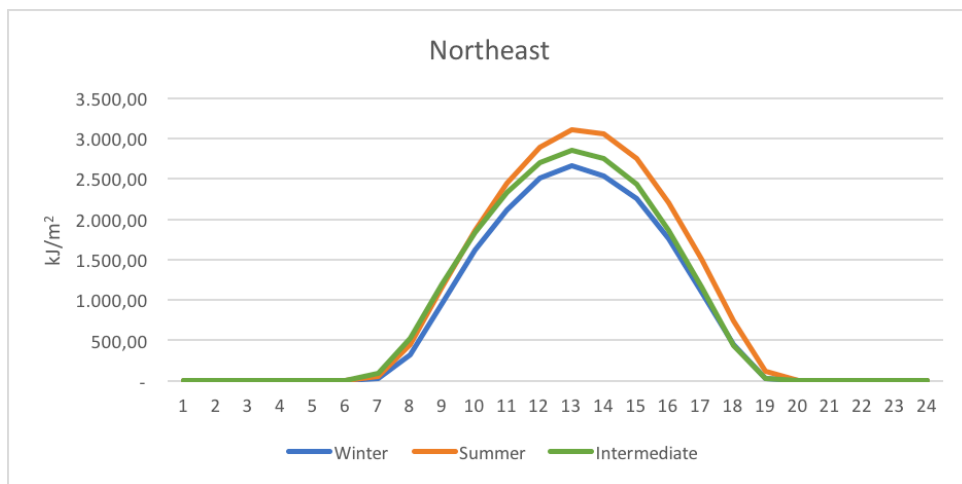


Figure 3 - Hourly insolation curves from the Northeast subsystem for each season.

There are two main contributing factors to the high solar potential of this subsystem, first, the average latitude of this region is higher than the previous two, causing the angle of incidence to be more perpendicular to the surface and shortening the path that light takes in the atmosphere. Second, this region is known for its dry weather and large portions of semi-arid land. Less rain and humidity means more time and intensity of sunlight.

The North subsystem is composed by the states of Maranhão, Tocantins, Pará, Amazonas, Roraima and Amapá¹ (ANEEL, s.d.). It shows an annual variation similar in module to the Northeast, however in an inverse direction. In this region, summer has the lowest irradiance and winter has the highest (Figure 4).

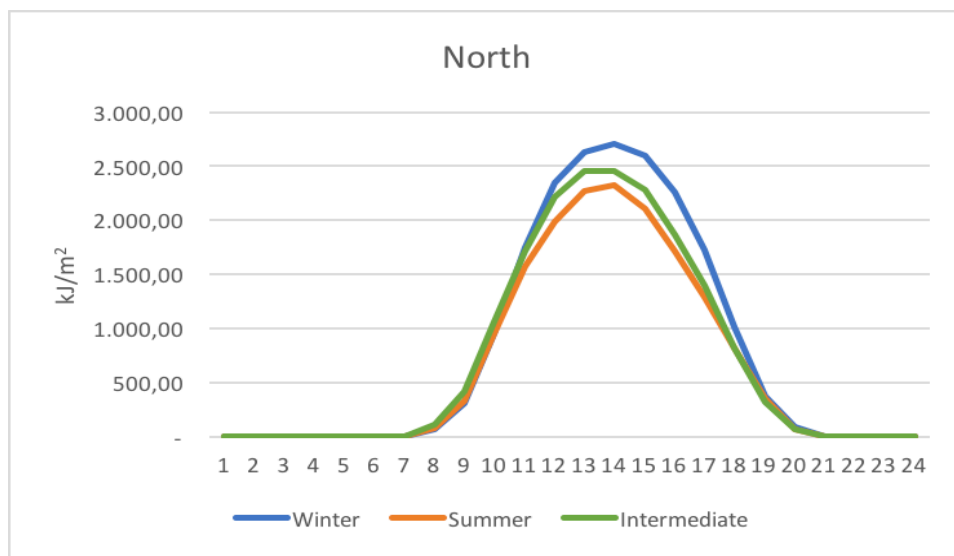


Figure 4 - Hourly insolation curves from the North subsystem for each season.

This is the northernmost region of the country, having parts above and below the line of the equator, meaning that in terms of solar angle of incidence there is very little variation throughout the year. The most important variable in this phenomenon is the difference between dry and rain season. The rain during the summer months is so constant

¹ Some areas of the country are still segregated from the unified power grid, however, these areas are going through the process of joining the national power grid.

and intense that causes a significant drop in average insolation. High humidity also contributes to this by scattering more light in the atmosphere.

4.2.- Comparison by Season

To better compare the solar potential of the different subsystems, this section will present the curves for each season compiled into 3 graphs.

During summer months, the Northeast subsystem has the highest insolation (Figure 5). During peak hours, the magnitude of the insolation can be up to 20% higher, on average, than the South or Southeast/Midwest. Whereas the North subsystem doesn't present itself as a good option for PV energy projects. Summer months have the highest energy demand (EPE, 2014) due to higher temperatures, so for RES policies, solar energy isn't the best option for the North.

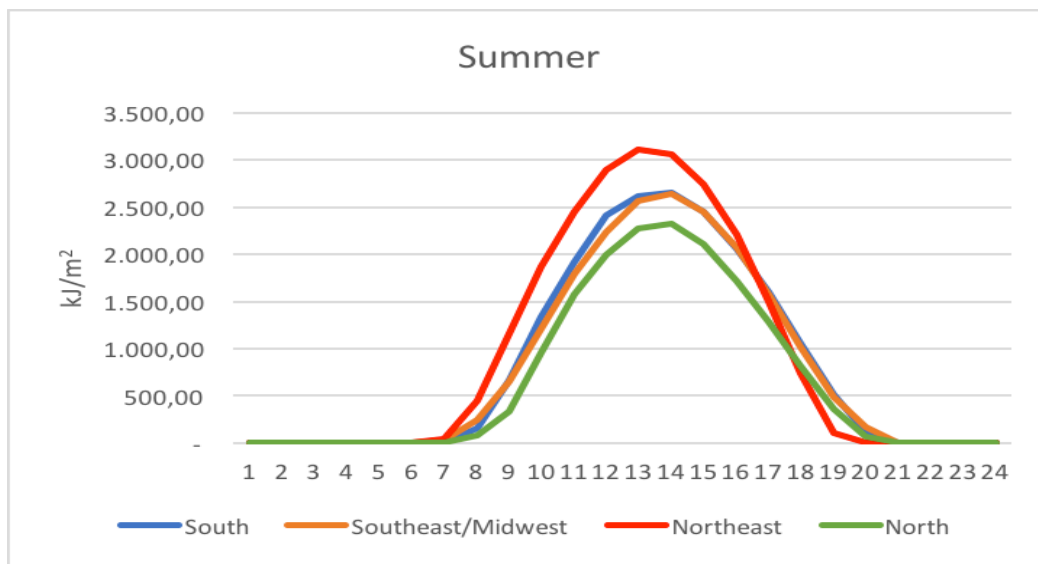


Figure 5 - Hourly insolation curves from summer for each subsystem.

As can be seen in Figure 6, the Northeast represents the highest insolation for the intermediate seasons, whereas the South represents the lowest. The Southeast/Midwest still occupies an intermediate position in terms of solar potential, along with the North, in this case.

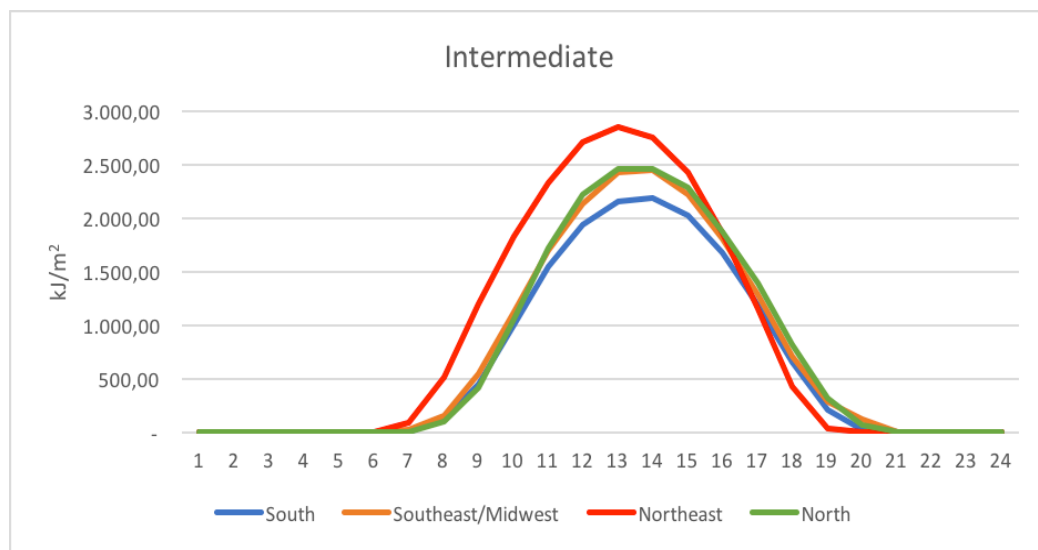


Figure 6 - Hourly insolation curves from the intermediate seasons for each subsystem.

Apart from the South subsystem, insolation has similar magnitudes during winter months (Figure 7). Based on the curves developed during this work, the two main candidates for developing PV energy projects are the Northeast and Southeast/Midwest respectively. The Southeast/Midwest has higher energy demand and capital concentration due to more energy-intensive economic activities and larger populations, whereas in the Northeast, both demand and capital is lower, but the solar potential is far greater. These differences might impact the types of PV projects and policies implemented in each of the regions.

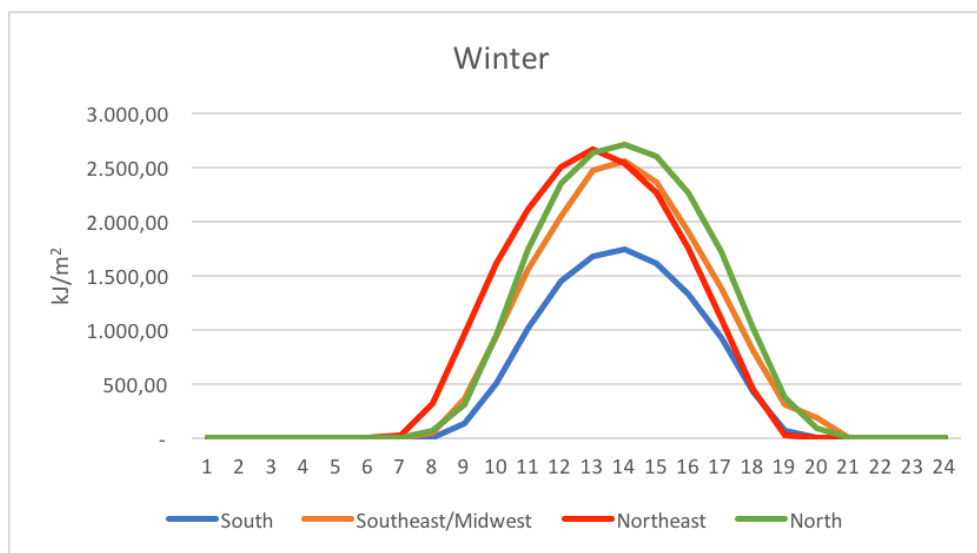


Figure 7 - Hourly insolation curves from winter for each subsystem.

5. Conclusions and Recommendations

Based on the information acquired in the elaboration of this work, the following conclusions were reached and some recommendations for future works have been listed in this section.

Brazilian solar potential is recognized, however unfortunately under-explored. Having in mind that PV energy is still settling and growing, and whose feasibility is constantly questioned, it's essential to take advantage of regions with high solar potential to set the foundation for larger adoption of RES, in particular, PV conversion. The information gathered by this study can assist in the planning and developing of PV systems, especially when considering distributed generation and energy policies.

Due to a higher energy demand and capital concentration, the development of PV projects is highly interesting. As for large urban areas, developing DG projects will be more feasible than large-scale PV plants. Whereas in the Northeast, the abundance of solar energy and the availability of ample space suitable for large PV plants and industrial complexes, the role of policies to stimulate the development of clean industrial complexes is key to a clean energy expansion and economic growth, nationally and locally.

Finally, having in mind the continuous expansion of knowledge, future works should consider using longer time series and other methods for analysing data, both statistical and not. An interesting subject is the complementing effect of dry and rainy seasons with PV and hydro generation, especially within the reality of tropical areas.

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