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Article

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Parametric Study of a Hybrid Renewable Energy Power Generation System in the Colombian Caribbean Region

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ABSTRACT

The global environmental problems have increased the interest in renewable energies, in this article a wind-solar hybrid system is proposed as an alternative for energy production. To carry out this study, the research was divided into three stages, the first one consists of determining the behavior of a solar and wind system, the second stage focuses on determining the ideal location to implement the hybrid system and the third stage determines the composition of wind and PV devices that offers greater efficiency. After completing the three stages proposed above, the optimal locations for the implementation of a wind-solar hybrid system are Simón Bolívar and Puerto Bolívar.

Keywords: Renewable Energies, Solar Energy, Wind Energy, Wind Potential
JEL Classification: Q42

1. INTRODUCTION

Renewable energies are an alternative to fossil fuels that can significantly reduce carbon dioxide emissions, including geothermal, solar, wind, biofuel and biomass; renewables have seen rapid growth in recent years due to cost reductions in wind and photovoltaic systems, in addition to a shift in energy policies in favor of renewables, they accounted for 26% of global electricity generation in 2018, however electricity only accounts for 20% of global energy demand, making the use of renewable sources in sectors such as transportation and thermal applications critical to accomplish the transition (Croutzet and Dabbous, 2021; Ahmed et al., 2021; Cole et al., 2021). In addition, it has been seen how corporations have increased their participation in the use and purchase of renewable energy, due to the pressure imposed by customers, investors and competitors, this behavior is expected to continue and increase, in the United States in 2010 the use of renewable energy in corporations was 5% by 2019 was approximately 13%, it is expected to exceed 20% by 2030 (O'Shaughnessy et al., 2021; Bistline et al., 2021).

The use of renewable energies not only offers environmental benefits, but also economic and political benefits as they are considered less volatile than fossil energy sources. Their integration into the energy grid requires work and planning in order to obtain a good synergy with other energy generation alternatives (Noorollahi et al., 2021), Wind and solar energy are widely used energy sources that have recently gained space due to their lower cost of implementation. The effect that the social aspect has on the development of alternative energy sources is seldom studied, which is why the social aspect of the development of alternative energy sources is rarely studied (Pavlowsky and Gliedt, 2021) The study of the local perception in the region of Oklahoma, USA, where the impact and perception of wind energy in the community that inhabits the region is studied, shows a mostly positive perception, which increases the knowledge of how it affects individuals and communities that host the turbines and the infrastructure related to the system.

It is important to know the effect that certain factors have on the energy production of a system (Diaz et al., 2021) performed a CFD (computational fluid dynamics) simulation to know the effect of the wake and the terrain on the energy generation of a wind system, by applying an interpolation-extrapolation methodology to the simulation the computational cost was reduced; from the results it was obtained that only taking into consideration the wake and the terrain adversely affects the results, while taking into consideration both parameters values close to the measured ones are obtained, also increasing the number of simulated direction sectors from 16 to 32 affects the results significantly. Wind energy can not only be harnessed on the ground, it can also be harnessed at sea, for this case Offshore wind turbines (OWTs) are used, (Wang et al., 2022) propose a design optimization for systems using this type of turbines using a differential evolution algorithm accelerated by the use of GPU, the optimized hybrid farm had 37.75% more energy output and 43.65% less wave load at the base of the wind turbines. Solar energy has been implemented to supply the existing energy demand in mining, since solar thermal and solar photovoltaic energy can be used to produce energy and heat needed in the mining process, so its applicability has been investigated in several academic works (Behar et al., 2021; Igogo et al., 2021).

The main contribution of this research lies in the determination of the energy potential with renewable sources, present in the Caribbean region of Colombia; thus, showing the key points for the development and installation of projects whose renewable sources in obtaining energy are solar or wind. In the following sections of the article, the technical parameters concerning the proposed hybrid plant design are provided, as well as all the information corresponding to solar and wind resource inputs, the fundamental equations and the research method used are also presented, and the information corresponding to the results of this research is shown, using graphs and data tables. Finally, the conclusions formulated at the end of this research are shown.

2. METHODOLOGY

To perform this study, the investigation was subdivided in three stages, which are related and are consequent. The first stage to perform consist to determinate the behavior of both wind and solar energy generating devices, in function of data collected from the meteorological stations up to 10 years of measurements. This stage is focused from an energetic perspective, which means only will take care of results like energetic production and renewable fraction, without data concerning costs, to estimate in which places the system will take more advantage of the renewable sources.

The second stage consists into realize a study to determinate in which place is more efficient the use of a hybrid system compounded by wind and PV system, working at the time. This stage is focused from an economic perspective, this time it will be take care of energetic production, renewable fraction, and results like total net present cost and the cost of energy, to determinate in which place the system will get the optimal behavior.

The third and most important stage is to determinate what composition of wind and PV devices are the most efficient, in function of the load demand and the characteristics of the selected place. Once this is finished, it will have the net power that the plant can develop and his optimal composition.

The first and second stage are calculated through specific equations, and the collected data from the results is digitalized in excel tables and presented as graphs. The third stage is more complex than his previous one, because the optimization process to be implemented here is through multi-objective solver from Optimtool complement of Matlab® and plotted as a Pareto front. However, before of this it is necessary to obtain data varying the number of devices for PV and Wind turbines for the selected place. Later these data are used in curve fitting complement of Matlab® to determinate the corresponding function for two main objectives of optimization (cost of energy and CO_2 emissions) which will be used in Optimtool.

The large-scale implementation of an energy production system based on non-conventional sources is important in the future because it can eliminate the dependence on fossil fuels for this purpose, and also directly confront the problem of global warming, thus increasing the quality of life of many populations around the world. This is why renewable energy is currently a growing and young field of research, technology, and production, projected to be the main axis of the first world countries in a few years (Adib, 2019).

Solar energy is a renewable energy source which is obtained from the solar radiation emitted and there are 3 methods of obtaining this resource: photovoltaic, photo-thermal, and thermoelectric. Of which the photovoltaic method stands out, since it is the method used to directly obtain electrical energy and consists of transforming solar radiation into electricity through photovoltaic panels. To date, photovoltaic panels are used as an autonomous system and currently these systems have been spreading in the industrial and commercial sector (Adib, 2019).

Wind energy is a resource which is obtained through the force of the wind, where the use of wind turbines or wind turbines are the most efficient and most used mechanism for obtaining this resource. This is produced by transforming the kinetic energy of the wind into mechanical energy using a wind turbine which transforms mechanical energy into electrical energy through a generator. One of the main trends or objectives in the development of wind turbines is the increase of the blade span, head height, and the increase of the total efficiency of the device, operating in coastal environments or even in the ocean, as well as reduction or braking mechanisms that help to maintain a constant speed in the turbine head to avoid overheating or failures due to vibrations (Adib, 2019).

2.1. Win Turbines Power Output Equations

The power of the wind passing through the wind turbine,, is expressed according to the equation (1).

$$\dot{W}_w = \frac{1}{2}\rho \cdot A \cdot v^3 \quad (1)$$

where ρ is the air density, A is the area displaced by the motor, and v is the wind velocity. The rotor shaft power is expressed according to the equation (2).

$$\dot{W}_s = C_p \cdot P_v \quad (2)$$

where C_p is the aerodynamic efficiency of the blades, which is a function of rotor speed ratio λ, and the angle of inclination of the blade β. The speed ratio of the rotor is given by equation (3).

$$\lambda = \frac{\omega_r \cdot R}{\upsilon} \quad (3)$$

where ω_r is the speed of the rotor shaft turbine power output $\dot{W}_s$ is expressed for the equation (4).

$$\dot{W}_t = \frac{1}{2}\rho \cdot A \cdot C_p \cdot \eta_m \cdot \eta_g \upsilon^3 \quad (4)$$

where η_m and η_g represent the efficiency of the gearbox and the generator respectively (Chen et al., 2018).

2.2. PV Output Power Equations

The power of a PV array $\dot{W}_{PV}$ can be calculated by the equation (5).

$$\dot{W}_{PV} = N_p \cdot I_{ph} \cdot V - N_p \cdot I_d \cdot V \cdot \left[exp\left(\frac{qV}{KTAN_s} \right) - 1 \right] \quad (5)$$

Where N_p is the number of photovoltaic arrays connected in parallel, N_s is the number of photovoltaic arrays connected in series, V is the output voltage of the PV array, q is the charge of an electron, K is Boltzmann's constant, A is the ideal junction factor which varies from 1 to 5 with 1 being the ideal value, T is the temperature of the solar cell. I_{ph} e I_d represent the photovoltaic current and the reverse saturation current, respectively I_{ph} in turn depends on solar irradiance and cell temperature, and can be calculated by the equation (6).

$$I_{ph} = [I_{scr} + K_i \bullet (T - T_c)] \bullet [S/100] \quad (6)$$

where I_{scr} is the short-circuit current of the cell at reference temperature, k_i is the short circuit temperature coefficient, T_c is the reference temperature of the cell and S is the solar irradiance at mW/cm^2. I_d depends on the temperature according to the equation (7).

$$I_d = I_c \cdot (T / T_c)^3 \cdot exp\left[\left(q \cdot \frac{E_g}{KA} \right) \cdot \left(\frac{1}{T_c} - \frac{1}{T} \right) \right] \quad (7)$$

where I_c is the reverse saturation current under conditions of T_c and E_g is the band gap energy of the semiconductor used in the cell (Singh, 2013).

2.3. Energetic Demand and Fundamental Variables

For the correct development of this research, it was necessary to use an energy demand profile that best fits the current events in terms of energy requirements in the region. The objective of establishing an energy demand does not obey in a truthful way to the current real demand of the Colombian Caribbean region; on the contrary, it is based on the establishment of a comparison parameter to which all the parameters corresponding to each of the locations must be submitted, using the previously proposed energy generation system. Figure 1 shows the type of profile used and its pre-established values (Budes et al., 2020).

It is also important to define the fundamental variables required by the software prior to the simulations. Table 1 shows the values concerning each of the mentioned variables. It is important to highlight that each of these values plays a fundamental role in order to avoid errors in the simulations, so it is recommended not to modify them if you want to replicate this simulation.

3. RESULTS AND DISCUSSION

In this section of the article, you can find in a clear and concise manner, the results and their respective interpretation for each of the phases previously described in the development process of this research.

3.1. Solar Radiation Assessment

Solar radiation is the main resource used by photovoltaic arrays to produce electrical energy, which is why Figure 2 shows the different values for incident solar radiation; it should be noted that the values for total solar radiation, which is the sum of direct radiation and diffuse radiation, are shown in Figure 2.

The brightness index is a value between 0 and 1 that represents the fraction of incident solar rays that manage to completely penetrate the atmosphere until reaching the ground, being 1 the value in which all of them manage to penetrate the atmosphere, and 0 in null value; this parameter is directly related to the climatic state of the area, so it tends to vary depending on the day and the time of the year.

Temperature is a resource that alters the operation of wind turbines, due to the modification of air density as a function of this, but in turn alters the operation of photovoltaic arrays in terms of energy delivery, which is why the values for the temperature of the region are presented in Figure 3.

3.2. First Stage: Energetic Perspective

In order to determine where in the Caribbean region of Colombia the installation of a hybrid wind-solar power generation system

Table 1: Parameters used in the simulation processes by HOMER Pro

Parameter	Value	Unit
Grid price*	0.2	USD/kWh
Simulation period	10	Years
Annual scaled average	24000	kWh/day
Pike	1833.2	kW
Discount rate*	8	%
Rate of inflation*	2	%
Wind turbine hub height	80	Meters
Grid CO_2*	0.1	kg/kWh
PV O&M cost per unit	10	USD/year
Wind O&M cost per unit	30000	USD/year

Figure 1: Load profile used for this case study

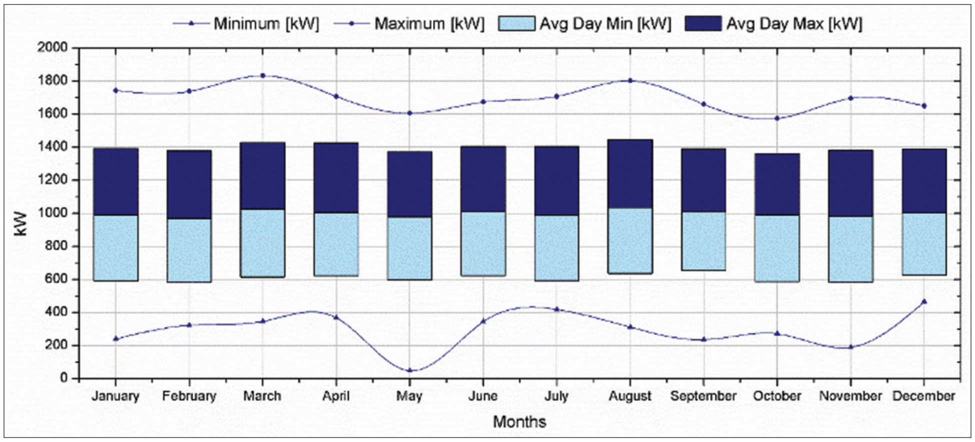


Figure 2: (a and b) Load Solar radiation data for the meteorological stations

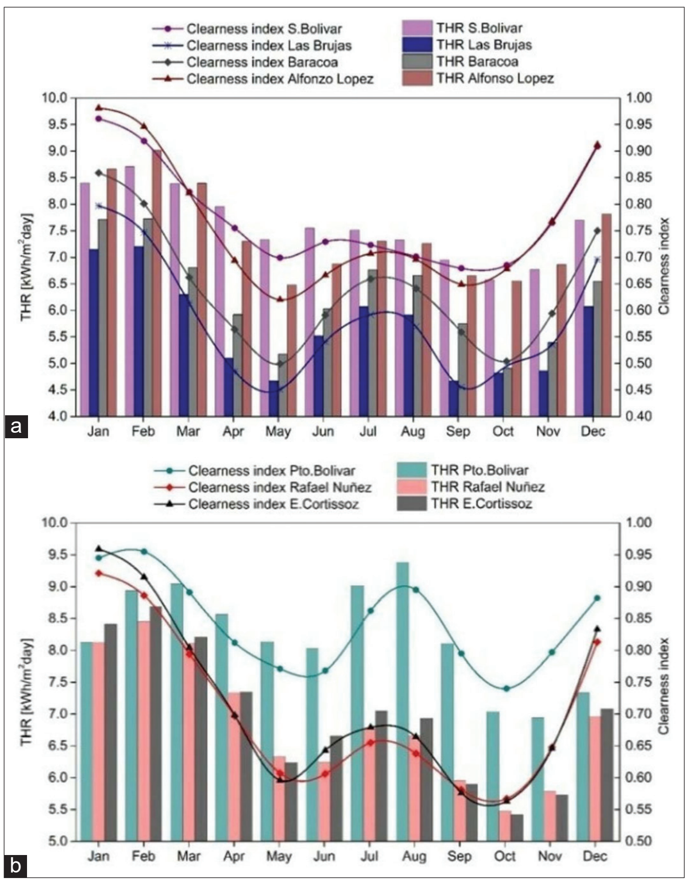
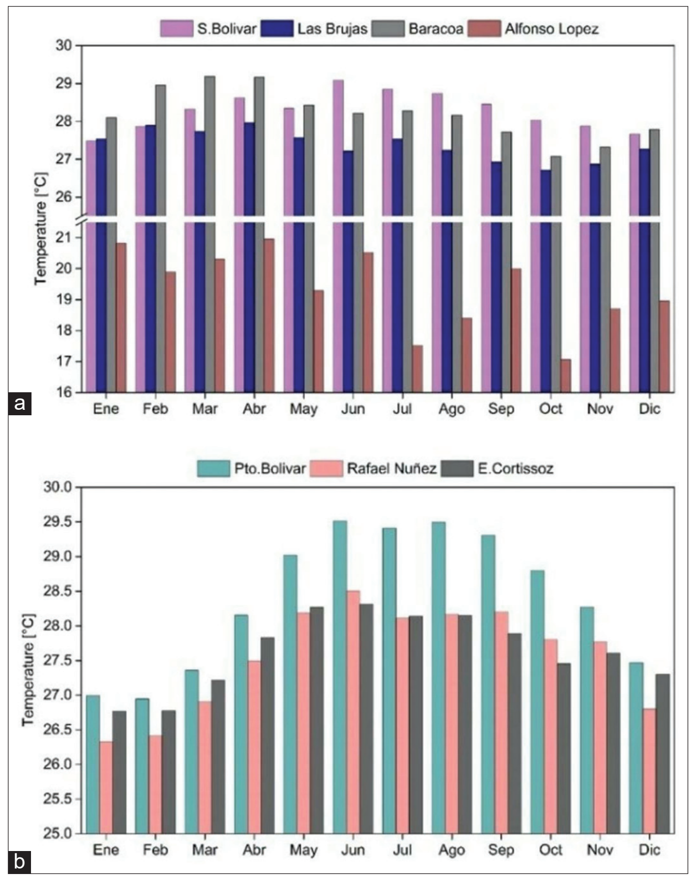


Figure 3: (a and b) Temperature data for the meteorological stations

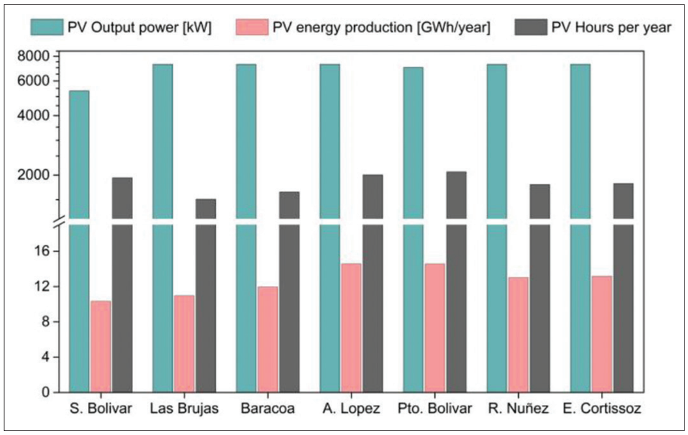


can work best, it is assumed that our previously proposed system is the optimal one to be installed. In that order of ideas, the results of the simulations of the first phase will show the technical specifications that our system must have to be considered as optimal according to the location in which it is located, considering only the variables of solar radiation, temperature, and wind speed, in each of the measurement stations. Similarly, a comparison is made between the nominal power of the photovoltaic system for each location, against the energy production produced by this system during a year, as shown in Figure 4.

From the above graph it can be seen that there is a variation between the nominal power and energy production for each location, likewise, it can be seen that the places where more energy is produced per year are Puerto Bolivar and Alfonso Lopez; however, this does not mean that they are the ideal locations. To determine in which locations the photovoltaic system works optimally, it is necessary to quantify the efficiency of these devices.

The fraction between the energy produced per year and the nominal power, in equivalent units, results in a value expressed in hours per year (h/year), whose value is nothing more than an estimate of hours in which, in theory, the system should work compared to the total hours of 1 year; thus, an ideal system is one that takes

Figure 4: Comparison between nominal system power and energy production per year of the photovoltaic system



advantage of the greatest amount of solar energy possible and can generate a good amount of electrical energy. Considering the above, it can be seen that the systems that develop a greater amount of "hours per year" are those located in Puerto Bolivar, Alfonso Lopez, and Simon Bolivar; which means that in these places our photovoltaic systems will take better advantage of solar energy.

After determining our optimal locations for the photovoltaic system, it is necessary to determine the optimal locations for the wind system. Since we have designated the use of wind turbines with a head height of 80 meters, and rated power of 1.5 MW, it is necessary to run a comparison between the number of turbines determined by the software to make the system "optimal," and the production per year that we have for each location, as shown in Figure 5.

It can be clearly seen that in 3 locations 3 wind units are required for the system to be optimal, in other 3 only 2 are required, and in Simón Bolívar a total of 9 are required, likewise, it can be seen that the locations that stand out for their energy production are Simón Bolívar, Puerto Bolívar, Rafael Nuñez, and Ernesto Cortissoz; However, in order to consider the ideal locations for the wind system, it is necessary to verify the fraction of energy produced by each wind unit, with the objective of determining in which location 1 unit can produce more energy than in any other location.

Considering the above, it can be clearly seen that Simón Bolívar, Puerto Bolívar, Rafael Nuñez, and Ernesto Cortissoz have the highest wind production indexes, among which Puerto Bolívar and Simón Bolívar stand out because they are also optimal locations for the photovoltaic system.

Knowing the ideal locations for the wind system, it's necessary to determine which of the aforementioned locations for both systems are ideal to take maximum advantage of both solar and wind energy, which is why it is necessary to analyze the percentage of the renewable fraction present in each of the aforementioned locations, as shown in Figure 6.

The renewable fraction of a system is nothing more than the fraction between the amount of clean energy produced against the total amount of energy demanded in our simulation, considering

Figure 5: Comparison between number of wind turbines and annual production for each location

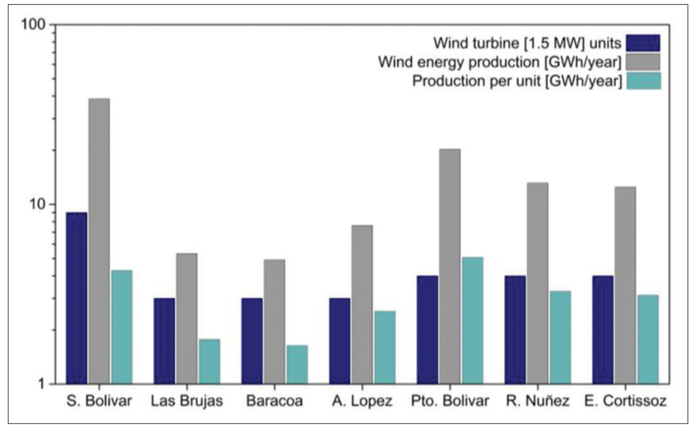
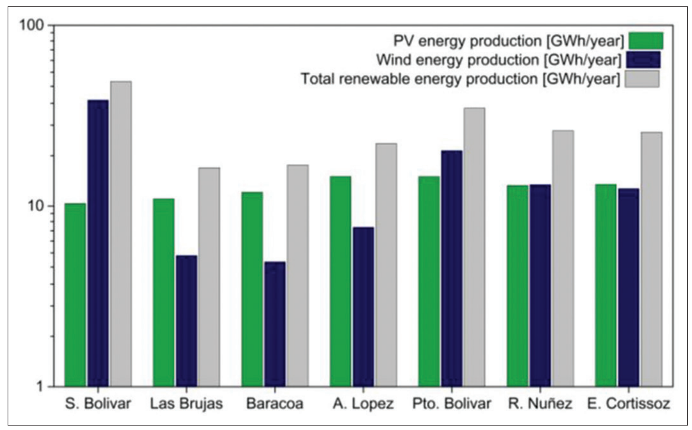


Figure 6: Comparison between production and renewable fraction for each location



that all the energy that the system cannot supply must be compensated with energy from coal-fired power plants or other means of conventional energy production.

Once the optimal location for the installation of a hybrid system of wind and solar production is found, it is possible to make modifications to the system in order to reduce production costs, which represents a reduction in the unit cost of energy and increases the quality of life of the potential beneficiaries of such a system.

Considering the locations selected above, and taking into account that the same energy demand was applied for all locations, it is assumed that the renewable fraction is directly proportional to the amount of clean energy produced in this case. Due to this, it can be clearly seen that the optimal locations for the installation of a hybrid wind-solar system are Simón Bolívar and Puerto Bolívar, which in turn will be the pilot locations for the development of phase 2 of this research.

4. CONCLUSIONS

The global environmental problems have increased the interest in renewable energies, in this article a wind-solar hybrid system is proposed as an alternative for energy production. To carry out this study, the research was divided into three stages, the first one consists of determining the behavior of a solar and wind system, the second stage focuses on determining the ideal location to implement the hybrid system and the third stage determines the composition of wind and PV devices that offers greater efficiency.

La Guajira has a high energy potential compared to other departments in the Caribbean region of Colombia, due to the high availability of the resources in question, which in turn is attributed to the relief of the terrain that does not pollute the air currents too much, and the low atmospheric concentration which favors that a large amount of solar radiation can be harnessed.

In addition, it is established that it is possible to use a hybrid generation plant using solar and wind devices to meet the energy demand of a particular region, and that this type of project is not only energy efficient, but also considerably reduces the emissions of polluting gases from coal-based thermoelectric plants that are mainly used in this region of Colombia. In this way, dependence on fossil fuels is reduced without altering energy production. This investigation also contributes a methodology to recreate this kind of studies on another location.

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