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Study of the Influence of load profile variation on the optimal sizing of a standalone hybrid PV/Wind/Battery/Diesel system

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Abstract

This paper presents a methodology to size and to optimize a stand-alone hybrid PV/Wind/Diesel/Battery bank minimizing the Levelized Cost of Energy (LCE) and the CO2 emission using a Multi-Objectives Genetic Algorithm approach. The main objective of this work is to study the influence of the load profile variation on the optimal configuration. The methodology developed was applied using solar radiation, temperature and wind speed collected on the site of Gandon located in the northwestern coast of Senegal. Results show that, for the all load profiles, as the LCE increases the CO2 emission decreases. For the all solutions, the LCE was lower for the load profile 3 than for the load profiles 1 and 2.

Keywords: Hybrid system, load profile, optimization,

1. Introduction

The use of fossil fuel has an impact on the environment and the cost of the fossil fuel is increasing due to their scarcity. However renewable energy such as solar energy and wind energy are available, inexhaustible and it can be used to produce electricity. In remote regions, far from grids, electrical energy is usually supplied using diesel generators. In the most cases, supplying demand energy using diesel fuel is so expensive and increases the amount of CO2 emitted. Indeed, the CO2 is the principal cause of the greenhouse effect. Hybrid system (PV/wind/diesel/battery bank) become competitive with the only diesel generator [1]. Moreover, in the most harnessing cases of the renewable energy, the use of the only solar

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energy or the only wind energy implies the increasing of cost of the Energy [2-5]. Thus, wind and solar energy can be used in combination with diesel generator making a hybrid PV/Wind/diesel/battery bank system.

Several methodologies to design optimal hybrid PV/Wind/Battery bank systems have been developed. In the works [6-9], the authors have used an iterative method of optimization making it possible to minimize the Annualized Cost of System (ACS). Those methods made it possible to study the performance of the hybrid PV/Wind systems. The performance of hybrid systems using genetic algorithms minimizing the cost of system was achieved by [10-12]. In these studies, authors have considered the only cost of system as an objective to optimize. Furthermore, the methods outlined in these works did not take into account all devices of system such as wind turbine, PV module, regulator, battery, inverter and diesel generator. Moreover, those works did not take into account the diesel generator, which can help to make hybrid PV/Wind/Diesel/ Battery systems more economic than the use of the only PV/wind/battery systems. Also, the CO2 emission was not evaluated in those works.

The main target of this paper is to design an optimal PV/Wind/Diesel/Battery hybrid system minimizing the Levelized Cost of Energy (LCE) and the amount of the CO2 emitted by the use of diesel generator using a multi-objective genetic algorithm approach. The influence study of the load profile variation on the optimal configuration will be done by using various real load profiles.

The decision variables included in the optimization process are the number of PV modules, the number wind turbines, the number of batteries, the number of regulators, the number of inverters, the number of diesel generators and the type of each device.

2. Model of the hybrid system components

Hybrid solar-wind-diesel power generation system coupled to battery bank consists of a PV module, a wind turbine, a diesel generator, a solar regulator a battery bank, and an inverter. A schematic diagram of the basic hybrid system is shown in Fig 1. The PV module and the wind turbine work together to meet the load demand. When the renewable energy sources are sufficient, the generated power, after meeting the load demand, provides energy to the battery bank up to its full charge. The battery supplies energy demand to help the system to cover the load requirements, when energy from PV modules and wind turbine is inferior to the load demand. The load will be supplied by diesel generators whether power generation by both wind turbine and PV array is insufficient and the storage is depleted.

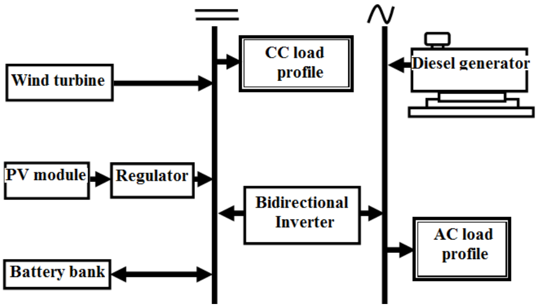

Fig.1. Bloc diagram of the hybrid solar-wind-diesel system

3. Methodology

In this paper, the Levelized Cost of consumed Energy (LCE) was considered. We do not consider the cost of the energy generating because in the remote village, most of the energy generated was lost. For example, if the PV generator or wind turbine generator produces energy during an hour when the electrical load is zero and the batteries are fully charged, then the energy produced by the PV generator or wind turbine generator was lost. In addition, the energy is also lost in the charge and discharge processes of the batteries.

The mathematical model of the components and the strategy of the battery management used in this study are detailed by the references [13,14]

4. Objective function

The objective function to minimize is the Levelized Cost of the consumed Energy (LCE) and the pollutant emission (kg CO2) which is the main cause of the greenhouse effect.

4.1. Economic model based on LCE concept

The optimal combination of a hybrid solar-wind-diesel-battery system makes the best compromise between the system pollutant emission and the cost of energy. According to the studied hybrid solar-wind-diesel-battery system, LCE represents the the levelized cost of the system (J(X) during the lifetime of the system (*integrating the levelized capital cost of components C_{acap}, levelized maintenance and operation cost of components C_{amain} and the levelized replacement cost of components C_{arep}*) divided by the energy consumption. it defined by Eq.1.

$$\mathrm{LCE} = \frac{\mathrm{J(X)}}{\mathrm{Eannual}} \tag{1}$$

J(X) is levelized cost of system given by Eq.2.

$$\mathrm{J(X)} = \mathrm{C}_{\mathrm{acap}}(\mathrm{X}) + \mathrm{C}_{\mathrm{amain}}(\mathrm{X}) + \mathrm{C}_{\mathrm{arep}}(\mathrm{X}) \tag{2}$$

C_{acap}, C_{amain} and C_{arap} are levelized capital cost, levelized maintenance and the levelized replacement cost of the components. The maintenance and operation cost (C_{amain}) take into account the cost of the fuel consumed by the diesel generator.

E_{annual} is the annual consumed energy (kWh/year),

$X=[N_{pv},N_{ag},N_{dg},N_{rg},N_{bt}, N_{inv}, T_{pv},T_{ag},T_{dg},T_{bt},T_{rg},T_{in}]$ is the vector of the decision of variables,

Where, $N_{pv},N_{ag},N_{dg},N_{rg},N_{bt}$, N_{inv} are the number of PV module, the number of wind turbine, the number of diesel generator, the number of regulator, the number of battery and the number ;

T_{pv}, T_{ag}, T_{dg}, T_{bt}, T_{rg}, T_{in} are the types of PV module, wind turbine, diesel generators, batteries, solar regulators and inverters.

4.2. Pollutant emissions

The parameter considered in this paper to measure the pollutant emission is the (kg of CO2). It represents the large percentage of the emission of fuel combustion [15]. Further, CO_2 represents the main cause of the greenhouse effect. So we evaluate the amount of the CO_2 produced by the use of diesel generator in the PV/wind/ diesel/battery system during one year of the operation of the system. It represents the second objective to minimize.

The fuel consumption of the diesel generator depends on the output power. It can be given by Eq.3:

$$\mathrm{Cons} = B \cdot P_{NG} + A \cdot P_{OG} \tag{3}$$

A=0.246 l/kWh and B=0.08145 l/kWh are the coefficient of the consumption curve, defined by the user [16]. These values were used in this study. The factor considered in this work to assess the emission of CO_2 was 3.15 kgCO2/l [17].

5. Hybrid system optimization method by using the genetic algorithms

The genetic algorithm code used in this work was developed by G Leyland [18] and A. Molyneaux [19] of the Ecole Polytechnique Fédérale de Lausanne, Switzerland. Originally, this multi-objective code was developed for energy systems with conflicting optimization criteria. In contrast with single objective optimization with one solution, multi-objective optimization aims at finding a set of Pareto solutions. A solution is said to be Pareto optimal if and only if it is not dominated by any other solution in the decision variable space. If solution X1dominates another solution X2, it implies that X1 is non-inferior to X2 for all the considered performance criteria but it is better than X2 for at least one criterion. All the points in the objective function space corresponding to the optimal solution form a Pereto front, which is useful to understand the trade-off between the performance criteria**.** The use of this tool makes it possible to design an optimal hybrid PV/Wind/Diesel/battery system which covers the load demand at a lower Levelized Cost of Energy (LCE) and a lower the amount of CO2 emitted.

This method has the advantage of maintaining the diversity of the population and making the coverage of the algorithm towards optima even difficult to find [20].

The PV generator and the wind turbine outputs are calculated according to the PV modules and the Wind turbine system model by using the specifications of the PV module and the wind turbine as well as the solar radiation, the temperature and the wind speed data [13, 14]. The battery bank with the total nominal capacity is permitted to discharge up to a limit defined by the minimum state of charge [13].

The initial assumption of the system configuration will be a subject of the inequalities constraints, given by inequalities 4.

$$\begin{cases} SOC_{min} \le SOC \le SOC_{max} = SOC_r \\ I_{rg} \le I_{rrg} \\ P_{ond} \le P_{rond} \end{cases} \tag{4}$$

Where: I_{rrg} is the nominal current of the designed regulators (A), P_{rond} is the nominal power of the inverter (W).

6 . Application on the site of Gandon

6.1. Presentation of the site

The previous presented methodology was applied using the solar radiation, the temperature and the wind speed which are collected for eight month on the site of Gandon (16.45° of longitude West, 15.96° of latitude North and 5 m of altitude) located in the Northwestern coast of Senegal. This region is characterized by a wind potential [21-23] adapted to small wind turbines (about 0. 2 kW to 10 kW) on the one side and on the other side, this region is characterized by a very sunny weather [24] which can be used to produce energy with the use of PV module.

In this area, an anemometers and a pyranometers have been installed for the purpose of obtaining wind speed and solar radiation data. Data acquisition system was used to record the parameters every one second. Then, the data are averaged over 10 minutes intervals and was recorded in the memory of the datalogger. To study the performance of the hybrid system, the used data were averaged over each one hour.

6.2. *Load profile*

The influence study of the load profile variation on the optimal configuration has carried out using three different load profiles having the same energy (94 kWh/d) (Fig.2).

The load profile n°1 shows that the power is high between 1h and 7h am and between 8h and 12h pm. That corresponds to the operating of domestic, public and commercial components (refrigerator, pumping water, mill, TV, radio, lighting, public house, bakery…) the peak of the power is of 7 kW observed at 10 pm. The lower power demand is observed during the day (between 8h am and 7 pm), that due to the public, commercial domestic equipment (refrigerator, TV, radio, lighting…).

The load profile n°2 gives the load of a village which fluctuation during the day corresponds to the operation of public, commercial and domestic equipments (lighting, refrigerators, domestic mill, welding machines, sewing machine, radio, TV, and other equipment). The elevation of the demand observed between 10h am and 10h pm corresponds to the use of the commercial, public and some domestic equipment (lighting, refrigerators, mill, welding machines, radio, TV). The maximum of the power is of 6 kW and the lowest is of 2 kW.

The load profile n°3 illustrates a low consumption during the night (lighting, refrigerator, TV, radio) and a high power demand in the day (pumping water, mill, welding machine, sewing machines, TV, radio…). The highest value of the power is of 5 kW and was observed at 10h am.

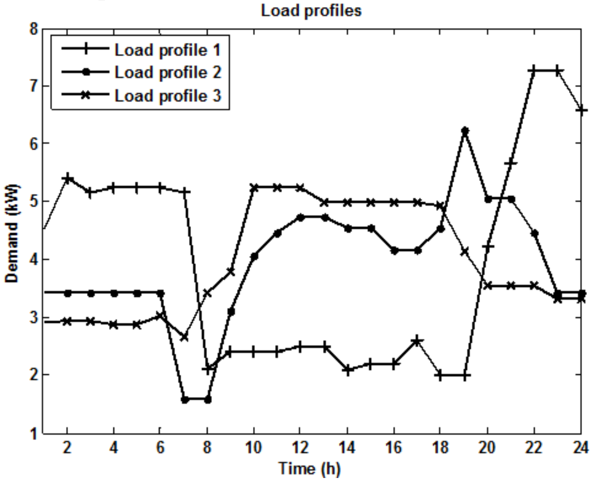

Fig. 2. Load profiles

6.3. *The components characteristics*

The specifications of the components used for design and optimization of the hybrid PV/wind/diesel/Battery are presented in Table 1. It was used five types of wind turbines and four types of

PV modules, batteries, regulators, inverters and diesel generators. for the optimal configuration, only one type of each component will be selected.

7. Results and discussions

The optimal sizing of PV/wind/diesel generator/battery hybrid systems minimizing the LCE and the CO2 emission were carried out using Multi-Objectives genetic algorithm approach. The results of optimization was appeared as an optimal Pareto front. Each solution of the best Pareto front was formed by a combination of hybrid systems and control strategy, with a different Levelized Cost of Energy and the CO2 emission.

7.1. Optimal Pareto front for the load profile n°1

Fig.3 shows the optimal Pareto front between the Levelized Cost of Energy (LCE) and the CO2 emission for the load profile 1. It can be noted that the decreasing of LCE implies the increasing of the CO2 emission. It is observed, also, that the diesel generator is more solicited for the right solutions on the optimal Pareto front than the left solutions. Also, the size of the wind turbine generator decreases from left solutions to right solutions. So, the battery bank becomes more and more solicited because of the diminution of the source of renewable energy, especially wind turbines, in systems.

To illustrate the results given by Fig.3, three solutions (A, B, C,) on different positions of the optimal Pareto front curve were selected.

The size of devices, the delivered energy, the LCE and the CO2 emission were given in the Table 2.

It can be noted that the cost of energy decreases by 49 % and 63 % when passing to solutions B and C from A. whereas, the CO2 emission increases by 2950.70 kgCO2/year and 7041.41 kgCO2/year. The energy from diesel generator was 0.05 %, 4 % 68% of the global output energy for the solutions A, B and C respectively. The remaining of delivered energy comes from renewable energy (PV generator and wind turbine generator). The excess of energy was 55%, 29% and 54% for the three solutions A, B and C. Also, it can be noted that the battery bank was less solicited. Indeed, the mean Stat of Charge of batteries (SOC) was 94%, 89% and 87 %. These values of SOC indicated clearly that the battery bank is more solicited for the right solution. The effect that the battery bank is less solicited for the solutions A can be explained by the size of the PV module and wind turbine generators which are higher for the solutions A than B and C. Thus, there is no need to discharge the battery regularly. The minimum state of charge of the battery bank (SOC_{min}) was 46.42% for the solution A and 60 % for solutions B and C.

7.2. Influence study of the load profile variation

The influence study of the load profile variation on the optimal configuration has been achieved. Results are presented as an optimal Pareto front.

It can be observed from fig.4 that, for the all load profiles, as the LCE increases the CO2 emission decreases.

Also, it is observed, for the all solutions, that the LCE was lower for the load profile 3 than the load profiles 1 and 2.

That can be explained by the fact that the load profile 3 is more adapted with the delivered energy from PV modules, Wind turbines.

To illustrate the obtained results, the 45th solution on the optimal Pareto front was selected for the three load profiles (1, 2 and 3).Table 3 depicts the size of devices, energy produced, the LCE and the CO2 emission for these tree solutions. It is noted from Table 3 that the LCE decreases by 14 % and by 34 % when passing from load profile 1 to the load profiles 2 and 3.

The solutions were hybrid PV/diesel/battery bank for the load profiles 1 and 3. However, it was hybrid PV/wind turbine/diesel / battery bank for the load profile 2.

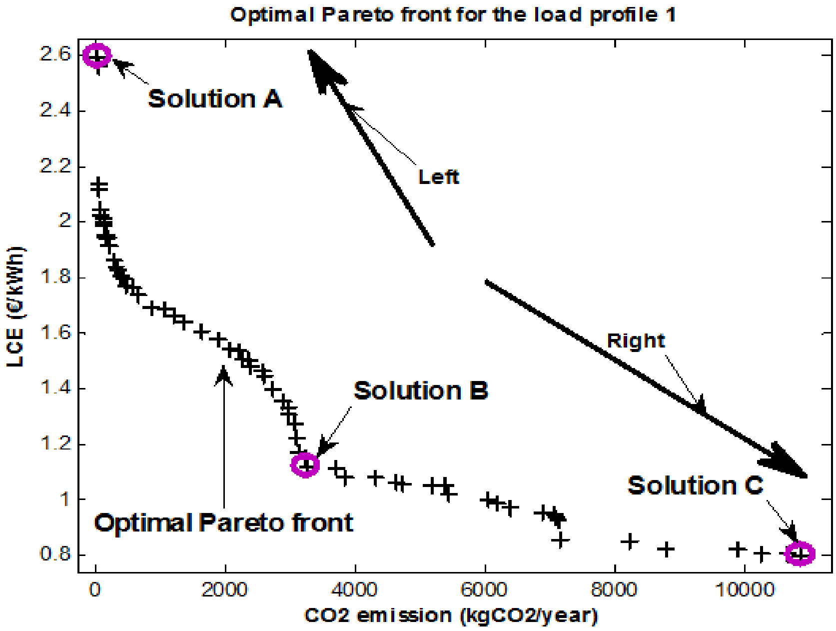

Fig.3. Optimal Pareto for the load profile 1

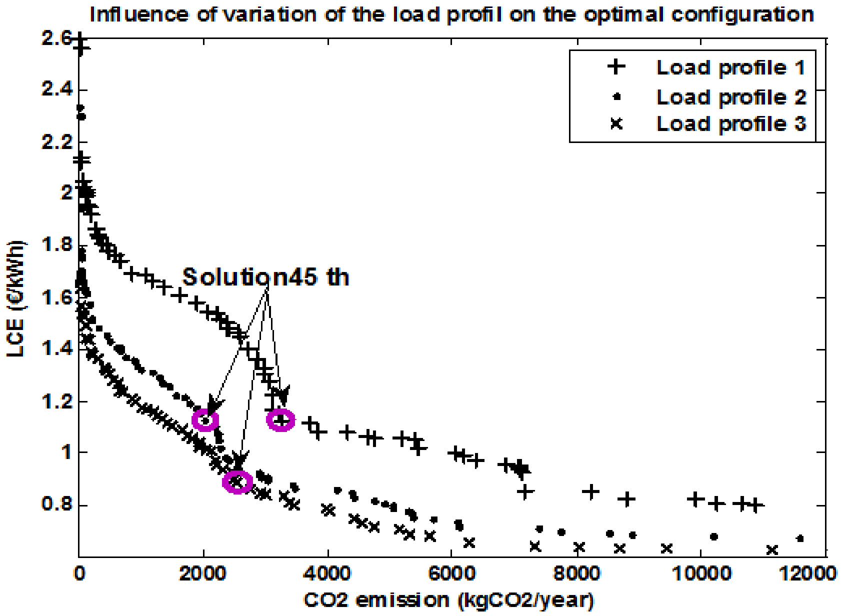

Fig.4. Influence of load profile on the optima configuration

Table 1: Specifications of components

Specifications of the wind turbine

Type of Wind turbines	Cut-in wind speed Vci (m/s)	Rate wind speed Vr (m/s)	Cut-off wind speed Vco (m/s)	Rated power Pr (W)	Output voltage (V)	Cost ( )
1	2	9	12	500	48	3051
2	3.5	11	13	600	48	1995
3	3.5	12	12	1500	48	2995
4	3	8	15	300	48	2615
5	2.5	14	25	5600	48	8870

Specifications of the PV module

Type of of PV module	Rate voltage (V)	Nominal peak powerk (W)	Current of short-circuit ¶(A)	Voltage of open circuit (V)	Fill factor	Cost ( )
1	12	75	4.70	21.50	0.74	590
2	12	80	5.31	21.30	0.71	540
3	12	100	6.46	20.00	0.77	559
4	12	150	8.40	21.60	0.74	900

Specifications of the batteries

Type of batteries	Nominal capacity (Ah)	Nominal voltage (V)	Cost ( )
1	80	12	195
2	100	12	215
3	200	12	416
4	720	2	2059

Specifications of the regulators

Type of the regulators	Nominal current (A)	Nominal voltage (V)	Cost ( )
1	30	48	230
2	40	48	250
3	45	48	289
4	60	48	295

Specifications of the inverters

Type of the inverters	Nominal Power (W)	Nominal voltage (V)	Cost ( )
1	3500	48	2799
2	2400	48	2165
3	4500	48	4185
4	5000	48	5350

Specifications of the diesel generators

Type of diesel generator	Nominal output power	Cost ( )
1	3050	668
2	4000	862
3	4600	879
4	4860	895

The diesel generator was more solicited for the load profile n°1 (1537 h of operation) than the load profiles n°2 (235h of operation) and n°3 (945h of operation). However, the battery is less solicited for this solution (load profile 1). The mean SOC was of 89% for the load profile 1 and 86 % for the load profiles 2 and 3. These results can be explained by the fact that the load profile N°1 solicited more energy in the night, period which the solar energy is not available. From Table 3, it can be noted that the energy delivered by diesel generators was 39 %, 6% and 23% for the loads n°1, n°2 and n°3 respectively. Then the diesel generator is less solicited for the load profile 2. That can be explained by the presence of the Wind turbine in the solution of the load profile 2.

The excess of energy for the three solutions (n°1, n°2 and n°3) was 29%, 13% and 10% (Table 3). It is lower for the load profile 3. That due to the fact that the load profile 3 is well adapted with the delivered energy than the two load profiles 1 and 2.

Form Table 8, we can, also, see that the minimum state of charge of the battery bank (SOC_{min}) was 60% for the tree load profiles. This SOC is superior to the SOC_{min} supposed equal 40%.

Table 2. Three solutions of the optimal Pareto front using load profile n°1

Solutions	Solution A	Solution B	Solution C
Number of PV modules	24	20	16
Number of Wind turbine	6	0	0
Number Batteries	112	84	44
Number of Regulators	1	1	1
Number of Inverters	4	4	4
Number Diesel generators	1	10	8
Type of Wind turbines	5	-	-
Type of PV modules	4	4	4
Type of Batteries	2	2	2
Type of Regulators	4	3	2
Type of Inverters	1	1	1
Type of diesel generators	3	3	3
Energy delivered by PV generator (kWh/year)	23138	19282	15425
Energy delivered by wind turbine (kWh/year)	26994	0	0
Energy delivered by diesel generators (kWh/year)	26.2	12421	34212
Operating hours of diesel h/year)	10	1537	2851
Excess of energy (%)	55	29	54
SCO_{min} (%)	46.42	60	60
Mean of SOC(%)	94	89	87
Levelized cost of energy (/kWh)	2.60	1.31	0.95
CO2 emission (kg CO2/year)	26.60	2977.36	7068.01

Table 3 : Influence of the load profile of the optimal configuration

Solutions according to the load profile	Load profile n°1	Load profile n° 2	Load profile n° 3
Number of PV modules	20	16	20
Number of Wind turbine	0	2	0
Number Batteries	84	44	52
Number of Regulators	1	1	2
Number of Inverters	4	3	1
Number Diesel generators	10	5	4
Type of Wind turbines	-	6	-
Type of PV modules	4	4	4
Type of Batteries	2	3	3
Type of Regulators	3	2	1
Type of Inverters	1	1	2
Type of diesel generators	3	3	1
Energy delivered by PV generator (kWh/year)	19282	15425	19282
Energy delivered by wind turbine (kWh/year)	0	9070	0
Energy delivered by diesel generator (kWh/year)	12421	1628	5709
Operating hours of diesel (h/year)	1537	835	945
Excess of energy (%)	29	13	10
SOC_{min} (%)	60	60	60
Mean of SOC (%)	89	86	86
Levelized cost system of energy (/kWh)	1.31	1.13	0.92
CO2 emission (kg CO2/year)	2977.36	2018.99	2451.80

8. Conclusion

A design of hybrid PV/wind/diesel/battery bank system has been carried out using Multi-objective genetic algorithm approach. The application of the developed methodology using collected solar radiation, temperature and wind speed data in the site of Gandon located in the northwestern of Senegal has allowed determining the optimal number of devices and the optimal type of each device assuring that the LCE and the CO2 emission are minimized. So the results were depicted on the optimal Pareto front.

The obtained results have showed that the increasing of the LCE implies the decreasing of the CO2 emission for the all load profiles.

The Wind turbine becomes less and less solicited with the increases of the size of the diesel generators in the systems.

For the all solution, the CLE was lower with the use of the load profile 3 than with the use of load profiles 1 and 2.

In the following, it would be interesting to perform modeling and optimization of the system incorporating the objectives of the availability and reliability constraints of components to achieve a more accurate assessment of the cost of system.

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