INFLUENCE FACTORS IN DESIGNING WATER PUMPING SYSTEMS FOR REMOTE RURAL CONSUMER

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Abstract - This paper aims to provide a series of technical aspects that arise in obtaining the best possible design for PV-based water pumping systems that supply isolated rural consumers, where the continuity of water supply throughout the year is a critical component. The main influencing factors on the design of a water pumping system have been identified and, in the end, the conclusions have been synthesized.

Keywords: water pumping system, design calculation, influencing factors, pumping parameters

1. INTRODUCTION

The technology of photovoltaic systems represents a source of clean and renewable energy for water management in isolated and rural areas. PV-based water pumping systems offer a sustainable and cost-effective alternative to traditional water pumping systems, especially in regions with limited access to electricity.

The main factors that can improve the design of a PV system for water pumping are well known: load and water assessment, site considerations regarding the PV panels, incorporating energy storage, monitoring the PV system performance etc.

This paper aims to highlight the specific influencing factors on the design of water pumping systems, a design based on an adapted mathematical model from [3], for the case of a rural consumer who requires continuous water supply throughout the year and is located in an area with long periods of unfavorable weather.

2. DESIGNING A COST-EFFECTIVE PV WATER PUMPING SYSTEM

To identify and highlight the key factors that significantly impact the design of a PV based water pumping system, we will utilize a calculus example.

The consumer in this case is a horse farm located in the area of Ineu, with an inventory of 70 heads. According to [1], this type of consumer requires a daily water consumption of $D_{cons/capita}$ = 50 liters per head of animal daily, which amounts to a total of requested water R_w = 3500 liters = 3.5 m^3 /day. The water requirement of the stock is usually calculated by multiplying the number of heads with the required amount per head of animal [1].

Due to the fact that this water demand is a critical component, as animals cannot be depraved of drinking water for more than one day during the winter season, it is necessary to equip the farm with a water tank that can provide the necessary water supply for at least 4 days of inclement weather.

Therefore, if the days of storage are considered to be DS = 4, the total daily water volume required will be the product of the daily requirement and DS, which gives the result of V_{water} = 14 m^3/day [1]. Therefore, will be used three standard water tanks of 5000 liters = 5 m^3 each, which gives a total reserve volume of V_{rez} = 15000 liters = 15 m^3/day, a sufficient value to cover the critical component. The results are summarized in Table 1.

Table 1. The daily water requirement at the consumer's end

Consumer requirements for DS = 4 days	[L/day]	[m³/day]
$D_{cons/capita}$	50	0.05
R_w	3500	3.5
$V_{standard}$	5000	5
V_{water}	14000	14
V_{rez}	15000	15

The drilling is carried out with a standard test well for drilling depths of up to 200m equipped with downpipes and PVC filters [2], having the characteristics shown in Table 2.

Table 2. Production and/or exploration well used

Technical features of the well	Value	Unit
Production column diameter	195	mm
Drill hole diameter	262	mm
Total depth	80	m
Static level	50	m

For **the pumping system**, a classic scheme is chosen with a submersible pump and water tanks located at a height of 3 m above the ground to ensure water pressure in the distribution system, Fig. 1.

It was taken into account that the height of the water in the standard tank of 5 m^3 is 1.8m and for the drawdown level the default value is 10% of the static level [3].

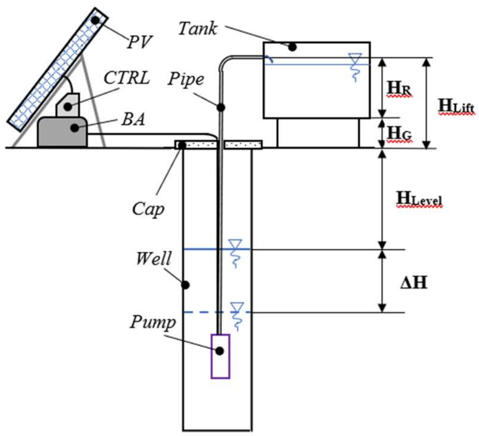

Fig. 1. Water pumping system layout

The technical characteristics for this pumping system are summarized in Table 3.

Table 3. Summary of the pumping system's technical features

Technical features of the pumping system	Symbol	[m]
Water level in Rz	H_R	1.8
Rez height level	H_G	3
Static lift	$H_{Lift} = H_R + H_G$	4.8
Static level	H_{Level}	50
Drawdown level	ΔH	5
Discharge head	ΔH_P	0*

* Default value for non-pressurized tanks [3]

The solar resource for a specific location must be estimated as accurately as possible, due to its significant impact on the sizing of the pumping system components. The parameter that quantifies the solar resource and is used in these calculations is peak sun hours [4] noted in this paper with S_{sun}.

In order to ensure the continuity of water supply to the rural consumer and taking into account its critical component, S_{sun} is determined both for the most unfavorable weather month and for the optimal inclination of the PV panel, as shown in Table 4.

Table 4. Insolation values at different tilt angle for the horse farm near Ineu, Bihor County [5]

Month	Peak sun hours S_{sun} [h/d]			
Tilt angle	**35°**	**45°**	**50°**	**57°**
January	1.97	2.03	2.06	2.1
February	2.95	3.07	3.1	3.11
March	4.14	4.21	4.21	4.18
April	4.85	4.73	4.63	4.45
May	5.76	5.49	5.31	5.02
June	6.28	5.91	5.68	5.31
July	6.64	6.31	6.08	5.72
August	6.19	6.01	5.87	5.6
September	5.02	5.04	5	4.9
October	4.23	4.39	4.43	4.43
November	2.33	2.46	2.5	2.53
December	1.63	1.73	1.77	1.8

It can be seen from tab. 4 that the most unfavorable month is December, so that for the optimal inclination of 57° it is considered S_{sun} = 1.8 [h/d].

The design calculation of the pumping system was then made by adapting the mathematical model from [3] to the design requirements imposed on the rural consumer in question. Thus, the following calculation steps result:

1) **Calculating the pumping system parameters:**

This is the preliminary stage where, based on the geometric and hydraulic characteristics of the well, the following parameters are calculated:

The number of operating hours t_P[h] = 10 [h]
Pumping time factor PTF = 5.6 [-]
Pumping rate PR = 347.2 [L/h]
Static Head H_a =59.8 [m]
Total Dynamic Head TDH = 63 [m]

The number of hours of operation of the pump exceeds the number of hours of insolation during the winter, this having as a consequence both the need to use the storage system in batteries and the use of the calculation formula from Table 5 for PTF.

Table 5. PTF depending on the type of pumping system [3]

PTF defaults values	
Direct connected pumps	**1**
With matching devices	**1.2**
With battery storage	T_P / S_{sun}

2) **Choosing the water pump:**

At this stage, with the obtained values for PR and TDH, we can choose the type of pump and the installed power based on the technical documentation provided by various manufacturers.

In this case, a submersible pump was chosen whose basic characteristics are presented in the Table 6.

Table 6. The chosen pup type characteristics [6]

Dankof-solar Flowlight submersible pump			
Characteristics	**symbol**	**value**	**[unit]**
Rated power	P_n	373	[W]
Nominal voltage	U_{nP}	24	[V]
Optimal current	I_n	8.4	[A]
Minimum current	I_{min}	3.8	[A]
Flow rate	D	4.5	[gallons/min]
Pump system efficiency*	η_{pump}	0.4	[%]

* If no data are available regarding the pump efficiency, the default value according to Table 7 will used.

Table 7. Pump systems efficiency [3]

TDH [m]	Pump type	η_P [%]
5	Surface rotary	25
20		15
20	Jet or submersible	25
100	Submersible or displacement	35
>100		45

3) Calculating the pumping system electrical parameters:

At this stage, the following parameters are calculated, necessary for sizing the electrical power generation systems for powering the pump:

Hydraulic energy W_{hydro} = 598.8 [Wh/d]
Array energy W_{PV} = 1497 [Wh/d]
The nominal system voltage U_n = 24 V
Amp hour load I_{day} = 62.4 [Ah/d]
Corrected amp hour load I_{day_cor} = 71 [Ah/d]
Design current I_{desg} = 39.4[A] **

** It will be calculated for the S_{sun} corresponding to each month of the year and the value for the month with the least insolation will be retained [3], Table 8.

Table 8. Design current of each month

Month	I_{day_cor}	S_{sun}	I_{desg}
January	71	2.1	33.8
February	71	3.11	22.8
March	71	4.18	17.0
April	71	4.45	16.0
May	71	5.02	14.1
June	71	5.31	13.4
July	71	5.72	12.4
August	71	5.6	12.7
September	71	4.9	14.5
October	71	4.43	16.0
November	71	2.53	28.1
December	71	1.8	39.4

4) Battery and battery bank sizing:

It has been chosen to use an energy storage system with battery accumulators, for which it is necessary to calculate the parameter:

BA required capacity C_{reqBA} = 420.7 [Ah]

From the manufacturers' catalogs, a lithium-based battery accumulator has been chosen, with the main characteristics summarized in Table 9.

This type of lithium-based battery accumulator was chosen due to its advantages over traditional lead-acid batteries, including a higher charge cycle (+4000h) and a longer lifespan, resulting in lower replacement costs.

Table 9. The chosen BA type characteristics [7]

Discover® Advanced Energy System (AES) LiFePO4			
Characteristics	**Symbol**	**Value**	**[unit]**
Rated Energy	W_n	5120	[Wh]
Nominal voltage	U_{nBA}	24	[V]
Rated capacity	C_{selBA}	200	[Ah]
Discharge cycles	Dsc	+4000	[h]

With these data, the following is calculated:

Number of batteries in parallel N_{parBA} = 3
Number of batteries in series N_{serBA} = 1
Total number of batteries N_{totBA} = 3
System BA capacity C_{sysBA} = 600 [Ah]
Usable system BA capacity C_{useBA} = 450 [Ah]

5) PV system sizing:

For sizing the PV system, the following parameter need to be calculated:

Derated design current I_{ddes} = 43.8 [A]

From the manufacturers' catalogs, Bauer solar panels are chosen for the PV system, and their technical specifications are presented in Table 10.

Table 10. The chosen PV panel characteristics [9]

Bauer Policristalin BS215-6P2			
Characteristics	**Symbol**	**Value**	**[Unit]**
Rated Power	P_{PV}	225	W
Rated module current	I_{nPV}	7.52	[A]
Module derated factor	DF	0.9	-
Voltage required for load	U_{load}	24	[V]
Highest temp PV voltage	U_{maxPV}	30	[V]
PV module scc current	I_{sccPV}	8.16	[A]
PV open circuit voltage	U_{opc}	36.1	[V]

Having chosen the PV panel, the following calculations can be performed:

Modules in parallel N_{parPV} = 6
Modules in series N_{serPV} = 1
Total PV modules N_{totPV} = 6

6) Controller CTRL sizing:

PV systems with BA must be equipped with controllers for charge regulation. It is oversized by 25% to support the current produced by the PV system at maximum irradiance [3]. For the considered system, a “Specility Concept ASC” Controller of 24V/12A nominal values has been selected [10].

7) Calculating the pumping flow and verifying the pumping flow condition

At this step, the pumping flow PF that the pump will provide with the PV system sized in step 5 is calculated, and it is compared with the water source capacity of the well S_W as follows:

Pumped water flow $Q_{p/d}$ = 4101.4 [L/d]
Pumping flow PF= 410.1 [L/h]
Source capacity S_W = 350 [L/d]

It is noticed that PF > S_W, so P_t will need to be increased to 12 hours of operation, so that pumping flow decreases under the 350 L/d.

The new obtained value of the pumping flow will be PF = 341.8 [L/d].

As a result, battery bank will be used both to cover the energy requirement for the 12 hours/day, as well as to power the submersible pump during inclement weather.

The water pumping system for the considered rural consumer is appropriately sized and will ultimately consist of:

- 6 PV panels on a fixed mount design, tilted at an angle of 57 degrees and oriented towards the South, capable of providing a current of 39.4A during the winter period in the most unfavorable month;

- 3 BA LiFePO4 connected 3 in parallel and 2 in series, 24 V with 450Ah usable capacity;
- 1 Dankof-solar Flowlight submersible pump, 24 V DC, 0.5 HP, capable of 1022 m^3/h flow at 8.4A optimum current;
- 1 Controller for BA charge/discharge regulation;
- 3 standard 5 m^3 water tank which provides the necessary water for 4 days of inclement weather, in which PV does not produce electricity.

2. THE FACTORS INFLUENCING THE DESIGN OF THE WATER PUMPING SYSTEM

The design of the water pumping system is influenced by various factors, having an impact on the project in different stages, as follows:

a) **Water source capacity**: in the preliminary stage, the water source capacity parameter (S_W) is particularly emphasized, as its accurate assessment determines the pumping time (t_P), pumping time factor (PTF) and pumping rate (PR).
Since total dynamic head (TDH) remains a constant due to the geometric characteristics of the well, the parameter that directly influences the installed power of the water pump remains pumping rate (PR), as shown in Fig. 2.

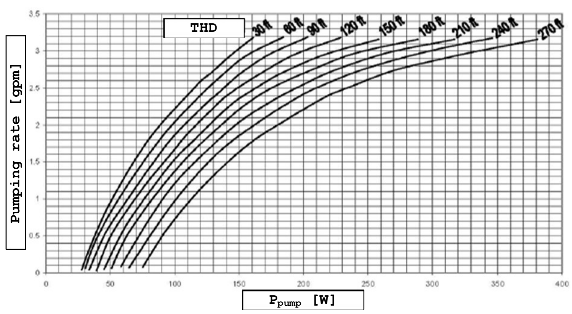

Fig. 2. Example of PV pump performance [8]

From step 6, it can be seen that it is often necessary to increase the number of operating hours of the pump in order not to exceed the capacity of the water source. In addition, the better the water source capacity (S_W), the lower the pumping time (t_P), even if the number of pump operating hours needs to be increased, Table 11.

Table 11. The influence of water source capacity on various pumping parameters

S_W [L/h]	350	450	550	650	750	800
t_P [h]*	12	9.2	7.5	6.4	5.5	5.2
PTF [-]	6.7	5.1	4.2	3	3.1	2.9
S_{sun} [h/Day]	1.8	1.8	1.8	1.8	1.8	1.8
PF [L/h]	341.8	445.8	546.9	640.8	745.7	788.7

* Increased values so that PF remains under S_W

b) **Static lift H_L [m]**: it depends on the water level in the pumping system reservoir at full tank (H_R) and the height of this reservoir from the ground (H_G), being their sum.
As the tank is higher above the ground, the THD increases, Fig. 3.

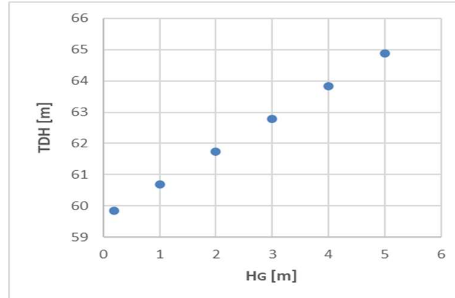

Fig. 3. TDH vs static lift at H_{level}=50m and allowance for friction of K_f = 0.05

This fact influences the energy needed to produce from the PV array and the load currents, but not the total number of PVs and BAs, as can be seen in Table 12 (except for the case when the tank is placed at ground level). This happens because when calculating these components, rounding BA and PV number is done upwards.

Table 12. The influence of H_G on TDH and electric parameters of the pumping system

H_G [m]	TDH [m]	W_{PV} [Wh/d]	I_{day_cor} [Ah]	N_{totBA}	N_{totPV}
0.2	58	1382	66	2	6
1	60	1422	68	3	6
2	61	1447	69	3	6
3	64	1472	70	3	6
4	63	1497	71	3	6
5	64	1552	72	3	6

c) **Static level H_{Level} [m]:** it directly influences both TDH and the energy needed to produce from the PV array, Table 13, and of course the higher the energy requred, the more PV panels are needed.

Table 13. Influence of static level on array energy

H_{Level} [m]	TDH [m]	W_{hydro} [Wh/day]	W_{PV} [Wh/d]	Pump type/ η[%]
10	17	158.2	633	Rotary/ 25
20	28	268.4	767	Submersible or Displace-ment/ 35
30	40	378.5	1081	
40	51	488.7	1396	
50	63	598.8	1711	
60	74	709.0	2026	
70	86	819.1	2340	
80	97	929.3	2655	
90	109	1039.4	2310	Displace-ment/ 45
100	121	1149.6	2555	
125	149	1424.9	3167	
150	178	1700.3	3778	
125	149	1424.9	3167	
150	178	1700.3	3778	
200	236	2251.1	5002	

d) **Pump system efficiency (η_P):** this parameter significantly influences the pumped water flow. In Fig. 4, it can be observed that for a water pumping system with 6 PV panels, 63 m TDH at a peak sun of 1.8, the difference is 600 liters per day when using a pump with an efficiency of 40% compared to one with 35% efficiency.

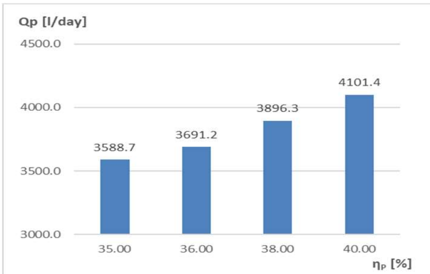

Fig. 4. Influence of the pump system efficiency on the pumped water flow

e) **Peak sun:** one of the most important factors influencing the design of a PV-based water pumping system is peak sun parameter (S_{sun}).
As shown in Fig. 5, for a 24 V pumping system with 40% pump efficiency and a THD of 63 m, a difference of 1.7 in S_{sun} leads to an improvement of pumped water flow ($Q_{p/d}$) by over 3800 l/day.

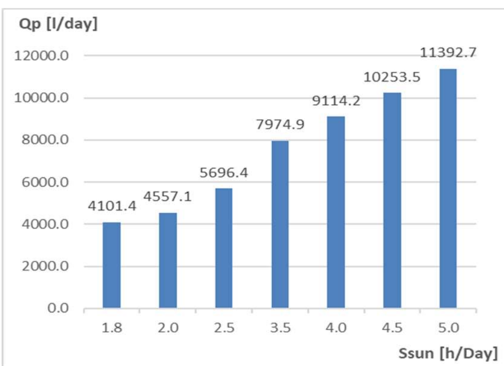

Fig. 5. Influence of the peak sun on the pump water flow

The current required to meet the system load (I_{des}) is also significantly influenced by the peck sun hours per day, as seen in Fig. 6.

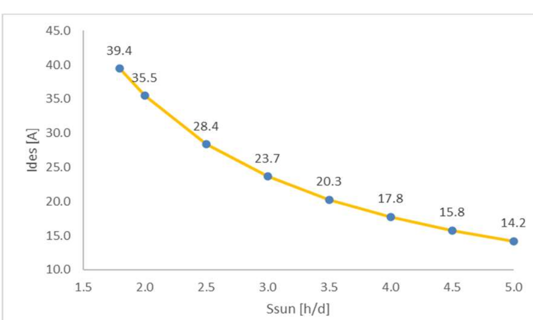

Fig. 6. Influence of the peak sun on the design current

The better S_{sun} is at the location of the pumping system, the more I_{des} is reduced, having a direct impact on the number of PV panels. As shown in Table 14, for the design of pumping system, the same 1.7 increase of the S_{sun} leads to halving the number of necessary PV panels.

Table 14. Peak sun hour per day influence of PV panels number

S_{sun} [h/d]	I_{desg} [A]	N_{totPV} [-]
1.8	39.4	6.0
2.0	35.5	6.0
2.5	28.4	5.0
3.0	23.7	4.0
3.5	20.3	3.0
4.0	17.8	3.0
4.5	15.8	3.0
5.0	14.2	3.0

f) **Storage days SD:** is one of the parameter that influence the total number of BA required for the pumping system, due to the fact that it has a direct impact on the electric energy capacity required for storage (C_{reqBA}) in the storage system, Table 15.

Table 15. Influence of SD on total number of BA required for 24 V pumping system

SD [d]	C_{reqBA} [Ah]	C_{selBA} [Ah]	U_n [V]	N_{totBA} [-]
1	105	200	12	2
2	210			4
3	316			4
4	421			6

The total number of BA required for the storage system is also influenced by TDH. For the considered pumping system with a 24 V LiPO4-based battery bank with a capacity of 200Ah each, the summarized values are obtained as shown in Table 16.

Table 16. TDH influence on total numbers of BA required for the water pumping system

TDH [m]	C_{reqBA} [Ah]	N_{totBA}
17	177.2	1
28	214.7	2
40	302.8	2
51	390.9	2
63	479.0	3
74	567.1	3
86	655.2	4
97	743.3	4
109	646.6	4
121	715.1	4
149	886.5	5
178	1057.8	6
149	886.5	5
178	1057.8	6
236	1400.4	8

g) **Nominal pumping system voltage:** determines both the nominal voltage of the water pump and the number of BA required for the storage system, Fig. 7 shows the results of the calculation made for different nominal voltages and different TDH.

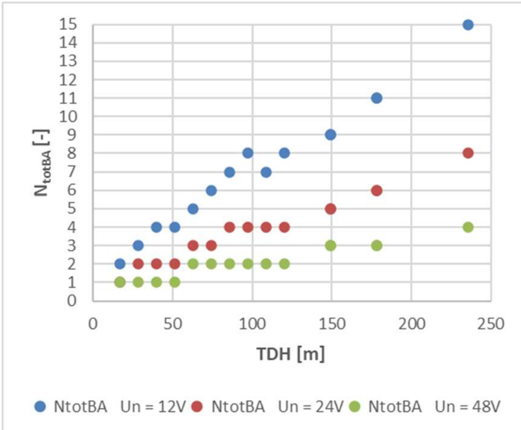

Fig. 7. The influence of the pumping system U_n on N_{totBA} at different TDH

CONCLUSIONS

Designing a PV water pumping system requires a thorough understanding of various technical parameters who are involved in the selection and sizing of its components.

Therefore, the dimensional characteristics of the well determine the type of pump required to obtain water (surface type, submersible type, displacement, one etc.).

On the other hand, the installed power in the pumping system is determined based on the capacity of the water source (S_W). An oversize of the installed power leads to a choice of a more expensive pump results in decreasing of the pumping system efficiency.

Furthermore, a higher installed power in the pump implies a greater amount of energy supplied from the PV system, leading to an over-sizing of the PV panels number and therefore increasing total system costs.

Also, S_W influences different pumping parameters of the system, the better this capacity of the water source is, the shorter the operating time of the pump (t_P), even if it has to be increased to satisfy the inequality $PF < S_W$.

If the pumping system is equipped with a water tank, its dimensional and placement characteristics does not influence the number of PV panels. What has a significant influence on this number is the total dynamic head, the higher the TDH, the more energy needs to be supplied from the PV system, thus requiring a higher number of PV panels and increasing in this way the total investment costs.

Due to the fact that TDH, in turn, depends on the water level in the well, it is clear that the higher the H_{Level}, the higher the TDH, and consequently, the number of PV panels will increase.

Another influencing parameter of a pumping system is the pump efficiency η[%]. The better it is, the higher the pumped water flow will be for a given location's peak sun hours.

Peak sun hours (S_{sun}) is a particularly important parameter because it influences the daily pumped water flow, the design current and the number of photovoltaic panels required for the system, thus:

- The better S_{sun} is, the more the pumped water flow increases and therefore, the system's ability to supply the consumer with water improves;
- Due to the fact that the current required to meet the system load (I_{des}) decreases with increasing S_{sun} an improved S_{sun} of the site leads to a smaller number of PV panels and therefore to a lower initial investment cost;

In most cases, pumping systems are designed without energy storage systems in an attempt to reduce costs. However, there are cases when these systems are necessary, either due to the need for year-round water supply or the need to increase the pumping duration during the day beyond the number of sunlight hours. There are also cases, as in the present work, when storage systems are necessary for both scenarios. Thus:

- In cases where water demand is a critical component for the consumer, a reserve is needed to supply water during periods of inclement weather. The larger the estimated number of days for water storage during such weather conditions (named in this paper SD), the higher the number of BA for battery bank is required, leading to an increase in the initial investment cost;
- The deeper the well, the higher the TDH, resulting in an increase in the required storage capacity and, consequently, an increase in the number of BA;
- The TDH and the selected nominal voltage for the water pumping system (U_n) directly determine the number of required BA: a higher voltage for the same TDH of the pumping system implies a lower number of required BA for battery bank.

In conclusion, when designing and sizing the components of a water pumping system for an isolated rural consumer, it is necessary to consider various parameters and factors that, due to their impact on the project, can lead to significant reductions in number of components and thus, in the reduction of initial investment costs. Thus, it can be obtained the best design for a PV based water pumping system to meet the requirements of an isolated rural consumer for a specific climate zone.

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