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Comparison of Two PV modules Technologies Using Analytical and Experimental Methods

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Abstract

Based on actual operating conditions, this paper focuses on the I-V characteristics of the two common types of silicon photovoltaic (PV) modules i.e. the polycrystalline and monocrystalline silicon modules using, for analysis the PV module behaviors, two mathematical models: the implicit model and the explicit model. In the implicit model, five coefficients are calculated analytically whereas in the explicit model, two coefficients are calculated from experimental measurements. These two models allow obtaining the I-V characteristics evaluating the marketed PV module quality and predicting its life and so its behavior according to environmental parameters changes. In the experimental part of this work, I-V characterizations of polycrystalline and monocrystalline silicon PV modules were performed to establish their explicit models. In real environmental conditions, considering illumination and temperature, and in addition to data provided by manufacturers, I-V characteristics are plotted and compared for the two models using codes developed under Matlab software environment. The results show a strong agreement between the implicit model and the experimental characteristics.

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Keywords: mathematical modeling and simulation; photovoltaic module; monocrystalline silicon panel; polycrystalline silicon panel; Current-voltage characteristic.

1. Introduction

The modeling of a photovoltaic (PV) module is an indispensable step for the evaluation of the efficiency of photovoltaic energy production systems. Modeling allows presenting the I-V characteristics of a module depending

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on a set of parameters (as temperature and illumination of PV cells) and estimating the optimal PV module performances. The description of the PV module behavior operating under actual irradiation level and temperature are generally based on two different models defined as the implicit and explicit models. These two models mainly differ by their respective I-V characteristics resulting of the number and origin of the considered parameters. In the following paragraphs, we consider and discuss these two models and the associated calculation methods that we have evaluated via Matlab developments for polycrystalline and monocrystalline silicon modules.

Nomenclature

E_1,T_1	illumination and temperature in the measurement conditions.
E_2,T_2	illumination and temperature in the standard or other desired conditions.
E_x	relative error (%)
I	pv cell or PV module current (A)
I_1, V_1	coordinates of points on the measured characteristics.
I_2, V_2	coordinates of the corresponding points on the corrected characteristic.
I_{mp}	maximum power current point (A)
I_{ph}	photocurrent (A)
I_s	diode saturation current (A)
I_{sc}	short-circuit current (A)
K	curve correction Factor (1,25×10-3 Ω/°C).
k	boltzmann's constant : $1{,}38\ 10^{-23}$ J / K
m	ideality factor of the module
m_c	ideality factor of a cell ($0 < m_c < 1$)
N_s	number of cells in series in PV module
P_{mp}	maximum power point (W)
q	electron charge: $1{,}6\ 10^{-19}$ C
R_s	series resistance
R_{s0}	slope at the end of the curve I (V) (Ω)
R_{sh0}	slope at the end of the curve I (V) (Ω)
R_{sh}	shunt resistance
T_c	cell temperature (° C)
V	pv cell or PV module terminals voltage (V)
V_{mp}	maximum power point voltage (V)
V_{oc}	open-circuit voltage (V)
V_t	thermal voltage (V)

2. PV panel modeling

2.1. Explicit model

The explicit model [1,2] is a very simple model based on experimentally measured parameters, in other publication [3] a mathematical model give the relationship between the current I and the voltage V, this model can describe the behavior of PV panel in operating conditions. These parameters are the short-circuit current, I_{SC}, the open-circuit voltage, V_{oc} and the voltage, V_{mp} and current, I_{mp} at the maximum power point. The characteristic equation of this model is defined as:

$$I = I_{sc}\left[1 - C_1\left(exp\left(\frac{V}{C_2 \cdot V_{oc}}\right) - 1\right)\right] \tag{1}$$

Where the two coefficients C_1, C_2 are to be calculated according to

$$C_1 = \left(1 - \frac{I_{mp}}{I_{sc}}\right) exp\left(-\frac{V_{mp}}{C_2 \cdot V_{oc}}\right) \quad (2)$$

$$C_2 = (\frac{V_{mp}}{V_{oc}} - 1)/\, ln\left(1 - \frac{I_{mp}}{I_{sc}}\right) \quad (3)$$

2.2. Implicit model

The implicit model can reproduce the behavior of the PV module taking into account the temperature and irradiance variations [3], that is based on the five physical and electrical parameters of the module, that are the photo-current, I_{ph}, the saturation current, I_s, the series resistance, R_s, the shunt resistance, R_{sh}, and the ideality factor. These parameters are analytically calculated from some experimentally measured variables at actual operating conditions. The characteristic equation related to this model is then [4, 5]:

$$I = I_{ph} - I_s\left[exp\left(\frac{V+R_s I}{mN_s V_t}\right) - 1\right] - \frac{V+R_s I}{R_{sh}} \quad (4)$$

Within:

$$V_t = \frac{KT_c}{q} \quad (5)$$

In order to solve Eq. 4, we have developed a computational code under Matlab software as indicated by the algorithm shown in figure 01. This model of I-V characteristics solving operate according to algorithm and allows us to plot I-V curves at any set of desired environmental conditions.

As indicated in figure 01, The resolution of the characteristic equation (4) requires at first to extract the five parameters characterizing the model. So from the experimental data retrieved from the test bench that are the current I, the voltage V and the power P of the PV module, these values inserted into the program that we had used to calculated the series resistor Rs0 and shunt Rsh0 by the method of least squares to the vicinity of the open circuit voltage Voc and the short-circuit current Isc respectively. These values are involved in the calculation of other parameters which are Iph, Is, Rs, Rsh and m by analytical equations, and then we introduced these settings in the characteristic equation (4); I= f(V,I) so that we can then solve numerically by a code developed under Matlab.

The validation of results obtained is made by their comparison with the experimental values, which results in the calculation of the root mean square error (RMSE) and the relative error Ex to the three main points Isc, Voc and Pm for different values of the parameters until the error is minimal, otherwise we repeat this operation. Finally, we plot the curves calculated with those corresponding experimentally.

1. Simulation and Experiments validation

For validate the comparison between calculated and experimental I-V characteristics, we used the error RMSE [6, 7] as a criterion of validation which allows to take into account all the experimental data to better adjust the curves [8] and the average of relative error of three parameters characterizing the PV module, which are the short-circuit current, the open-circuit voltage and the peak power.

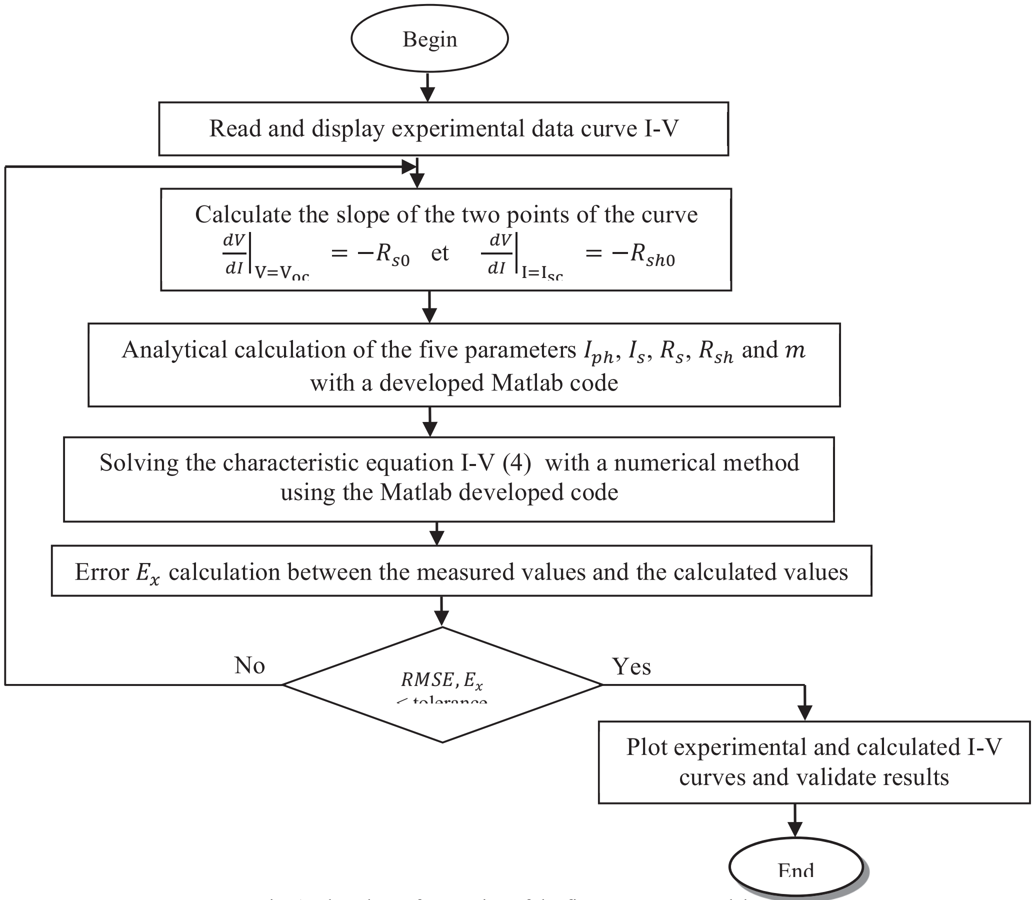

Fig. 1. Flowchart of extraction of the five parameters model.

According to the other developed Matlab code, we introduce the experimental voltage values in volts and we calculate the current values in each model. By the comparison between the experimental current and the calculated current for the same voltage value V, we get the RMSE. Similarly, the calculation of relative error is done by comparing calculated data (the short circuit current, the open circuit voltage and the maximum power values) with the same experimental parameter values respectively. Formula's relative error E_x and $RMSE$ calculating are as follow:

$$RMSE = \left[\frac{\sum(I_{cal}-I_{exp})^2}{N}\right]^{\frac{1}{2}} \tag{6}$$

Where: I_{cal} and I_{exp} are respectively calculated and measured current (A), N is the number of data points for each characteristic I (V).

$$E_x = \frac{X_{cal}-X_{exp}}{X_{exp}} \cdot 100\ (\%) \tag{7}$$

Where: X_{cal} and X_{exp} are respectively the calculated and measured values of I_{sc}, V_{oc} and P_{mp} parameters.

Experiments were done on the marketed BP Saturn and BP solar modules as indicated in table 01. Figures 2 and 3 present experimental and calculated I-V curves obtained through the explicit model applied to both BP Saturn and BP solar modules for different irradiation levels due to different temperatures of 25°C and 45°C.

Table 1. Summarized of the marketed PV modules characteristics

Technologies	Module	P_{mp} [W]	V_{mp}[V]	I_{mp} [A]	V_{oc} [V]	I_{sc} [A]	N_s	N_p
Si-Monocristallin	BP Saturn	85	29,2	2,3	35,9	3,0	60	1
Si-Polycristallin	BP Solar	160	35,1	4,55	44,2	4,8	72	1

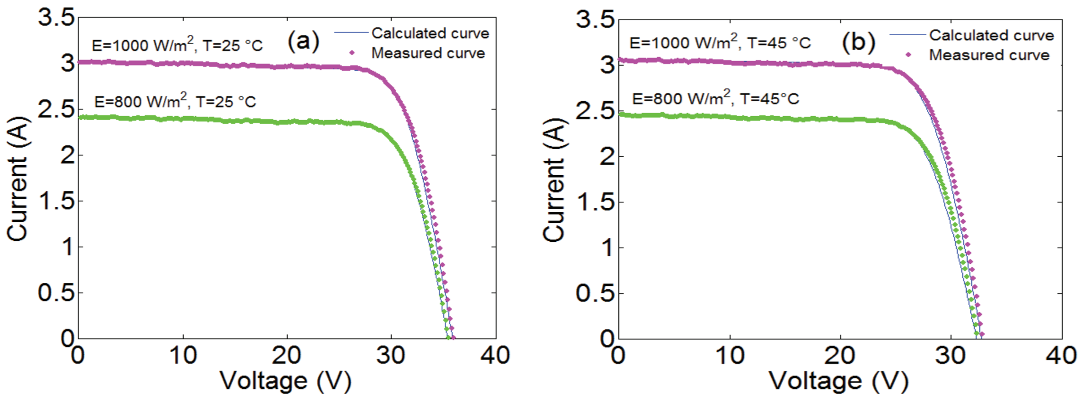

Fig. 2. (a) experimental and calculated I-V curves by applying the explicit model to a module BP Saturn for different irradiation levels at a fixed temperatures of T=25 °C; (b) at T=45 °C

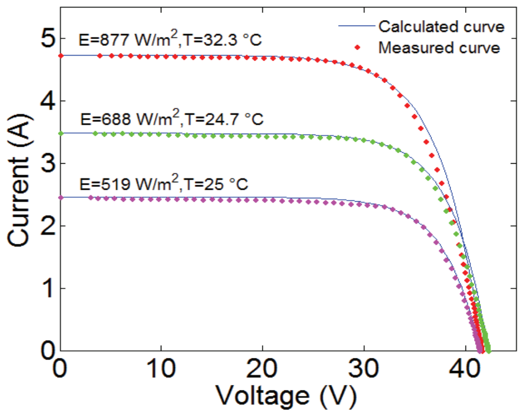

Fig. 3. Experimental and calculated I-V curves by applying the explicit model to a BP Solar module for different temperatures and irradiation levels.

According to figures 2 and 3, we can note that for different illuminations and temperatures, the RMSE varies between 0.053 and 0.083 for the mono-crystalline PV module and between 0.040 and 0.155 for polycrystalline PV module by using the explicit mathematical model.

The results of the application of implicit mathematical model for PV modules modelling are depicted in figures 4 and 5. For the same simulations parameters, the RMSE varies between 0.023 and 0.042 for the mono-crystalline PV module and between 0.073 and 0.124 for polycrystalline PV module. Thus, the second model present a minimum deviation relating to the explicit model. Therefore, and for the implicit model, we note that the calculated I-V characteristics are with a strong agreement with experimental characteristics.

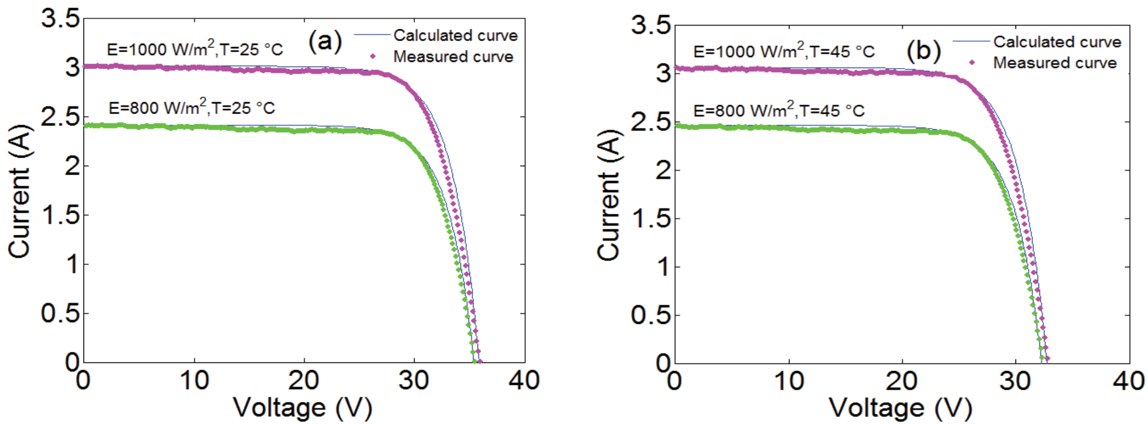

Fig. 4. (a) experimental and calculated I-V curves by applying the implicit model to a module BP Saturn for different irradiation levels at a fixed temperatures of T=25 °C; (b) at T=45 °C

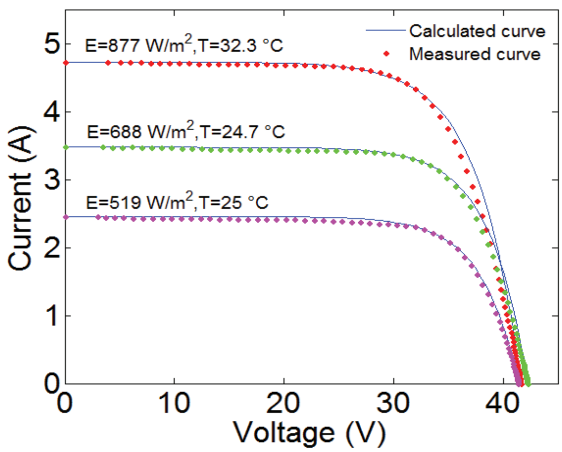

Fig. 5. Experimental and calculated I-V curves by applying the implicit model to a BP Solar module for different temperatures and irradiation levels.

The IEC 891 standard [9-12] gives procedures that should be followed for temperature and irradiance corrections to the measured I-V characteristics of crystalline silicon photovoltaic devices only. The translation of array measurements to STC is done by application of so-called mathematical procedures for temperature and irradiance correction [11,13]. The measured current-voltage characteristic shall be corrected to Standard Test Conditions (STC) or other selected temperature and irradiance values by applying the following equations:

$$I_2 = I_1 + I_{sc}\left(\frac{E_2}{E_1} - 1\right) + \alpha_{I_{sc}}(T_2 - T_1) \quad (8)$$

$$V_2 = V_1 - R_s(I_2 - I_1) - K \cdot I_2(T_2 - T_1) + \beta_{V_{oc}}(T_2 - T_1) \quad (9)$$

With:

α_{Isc}, β_{Voc} current and voltage temperature Coefficients of the test specimen in the standard or other desired irradiance and within the temperature range of interest ($\beta_{V_{oc}}$is negative).

Through a calculation code developed under Matlab, this method allows us to extrapolate I-V characteristics at any irradiance and temperature referred to the STC conditions or any other desired point. Figures 6 and 7 illustrate the I-V characteristics extrapolated from the experimental curves tanked as reference. Control measurements on PV generators should aim at keeping both uncertainties as low as possible. This is because the overall measuring uncertainty has to be added to the tolerance of fabrication given by the manufacturer when specifying the level of acceptable reduced array output. This level of acceptance (LOA) is the sum of both uncertainties.

Chenlo's method [14,15] is also simplified method to characterize crystalline PV modules, that is a good tool to extrapolate I-V curves at any operating point referring to experimental data. Translated curves from (V1,I1) point to (V2,I2) point obey the following equations:

$$I_{sc2} = I_{sc1} \cdot \frac{E_2}{E_1} + \alpha_{I_{sc}}(T_2 - T_1) \quad (10)$$

$$V_{oc2} = V_{oc1} + mV_t . ln\left(\frac{E_2}{E_1}\right) + \beta_{V_{oc}}(T_2 - T_1) \quad (11)$$

Translations formulas are:

$$I_2 = I_1 + \Delta I_{sc} \quad (12)$$

$$V_2 = V_1 + \Delta V_{oc} \quad (13)$$

Where:

$$\Delta I_{sc} = I_{sc2} - I_{sc1} \quad (14)$$

$$\Delta V_{oc} = V_{oc2} - V_{oc1} \quad (15)$$

α_{Isc}, β_{Voc} and m are PV module parameters. In the case of PV cell parameters, we have to consider $\alpha_{I_{sc}} = \alpha_{T_c} \cdot N_p$, $\beta_{V_{oc}} = \beta_{T_c} \cdot N_s$, $m = m_c \cdot N_s$

As indicated in figures 6 and 7, for a same reference curve either of E=1000 W/m2 and T=25°C, or of E=800 W/m2 and T=45°C we observed that the two methods are identical, i.e give the same relative error in the vicinity of I_{sc} between the calculated and the measured value, but we note at the first reference curve, that the difference of relative error is for -0.88 to -0.30 % by IEC 891 method and for 0.35 to -1.52 % by simplified method to the vicinity of the V_{oc} respectively, and for -1.14 to -0.88% by IEC 891 method and for -2.31 to -2.15 % by simplified method to the vicinity of the P_{mp} respectively. And for the second reference curve that the relative error varied for -2.43 to -1.42 % by IEC 891 method and for -1.30 to -0.31% by simplified method to the vicinity of the V_{oc} respectively, and for 1.27 to 1.76 % by IEC 891 method and for 2.47 to 3.16 % by simplified method to the vicinity of the P_{mp} respectively. Calculated I-V curves within the IEC 891 standard gives a good results comparing to the simplified method when compared to the experimental curves. The simplified method express a large error compared to the IEC891.

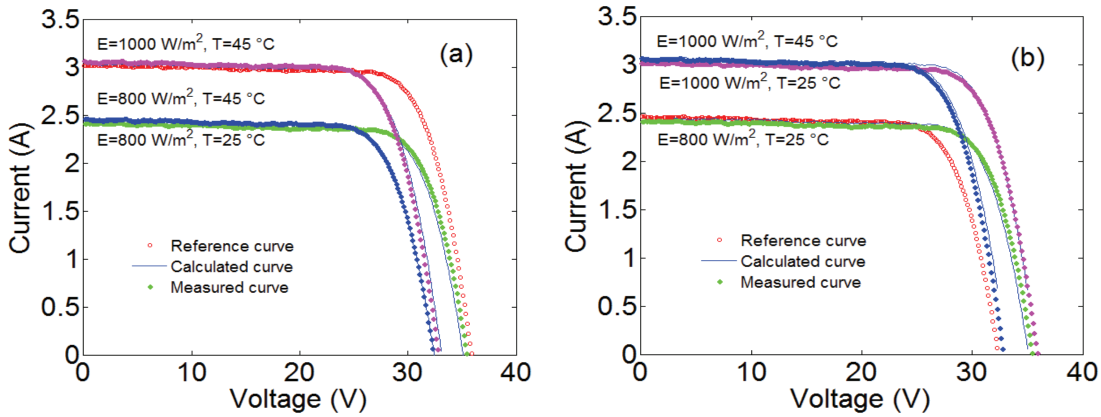

Fig. 6. (a). measured and calculated curves by translation with the reference curve according to the IEC 891 at E=1000 W/m^{2}and T=25 °c , (b) at E=800 W/m^2 and T=45 °c

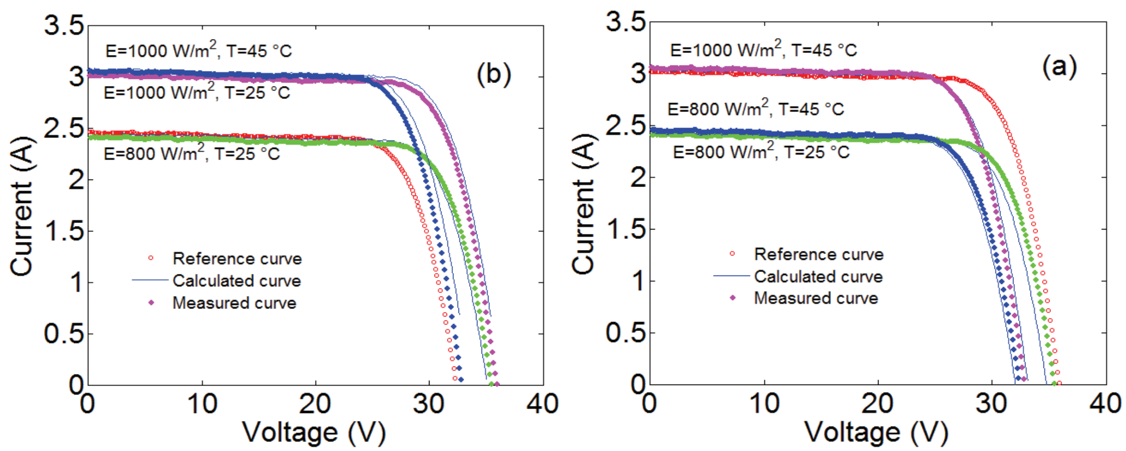

Fig. 7. (a) measured and calculated curves by translation with the reference curve according to the simplified method at E=1000 W/m^{2}and T=25°c , (b) at E=800 W/m^2 and T=45 °c

4. Conclusion

Characterization by comparing two types of silicon-based photovoltaic modules in the actual operating conditions: monocrystalline silicon and polycrystalline silicon module is widely discussed. The parameters involved in the physical model are introduced by the experimental data of the manufacturer and characterization lead to the selection of the appropriate mathematical model.

This study leads to conclude that the five parameters model is better and more accurate than the explicit model. By cons, in order to translate the characteristic curves from an operating point to another one in different operating conditions, it is preferable to use the method according to IEC 891. This one seems more convenient, since the scrolling curves reproduce faithfully the experimental curves.

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