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Characteristic and Efficiency Analysis of Storage-type Solar PV/Thermal Hybrid System

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Abstract Storage-type solar PV/thermal hybrid system added a water tank below the PV panel directly is to cool the surface of PV chip and reuse the waste heat. Solar test equipment was set up to adjust irradiation amount of halogen lamp to light on solar PV board and measure the I-V curves of the PV panel simultaneously. Surface temperature of PV panel and water temperature of water tank are measured respectively by infrared thermal imager and thermocouples. By altering the irradiation of 600~900W/m^2 at a 30° inclination angle of PV panel, the experience data of storage-type solar PV/thermal hybrid system can be got, total efficiency transformed by photovoltaic efficiency and hot water efficiency of PV/thermal hybrid system can be analyzed. The results show that total efficiency of storage-type solar PV/thermal hybrid system is more excellent as compared to the pure photovoltaic efficiency. The hot water efficiency of PV/thermal hybrid system from recycling waste heat gets 38~40%. If the electric/heat energy conversion efficiency is about 0.38, total efficiency transformed obtains more efficiency about 14~15% from the recycling the waste heat. The total efficiency of storage-type solar PV/thermal hybrid system is almost 4 times than photovoltaic efficiency in experimental surrounding.

Keywords PV/thermal, Storage-type, Total Efficiency

1. Introduction

Solar PV panel has been considered as the best renewable among the developable energy. The related technological application matures gradually. When solar PV panel is shined, the surface temperature of solar PV panel is increased. With the impact of heat, PV efficiency drops and lifetime cuts down also. Solenki et al. [1~2] set up a V-trough PV module to let the reflected lights fall on the PV panel inside the V-trough PV module to get its efficiency. The efficiency of 10.57% in normal solar PV panel can be measured at the sunlight amount of 750W/m^2, while the efficiency of 17.1% in V-trough PV module can be presented. Akbarzadeh and Wadowski [3] set up a cooling PV chip system, which focused sunlight with its reflector and cool down the surface temperature of the chip with cooling fins and heat pipes in the back of the PV chip. The surface temperature of the chip decreased 20℃, and the output power increased 10W.

Many scholars referred to the research that solar PV panel can be cooled down with water to improve its efficiency [4~6]. Krauter [7] set a water tank above PV panel with multiple water pipes releasing water through the upper surface of the panel to cool it down. The surface temperature of the panel decreased obviously.

Combining solar PV panel with solar heat collector is another concept to improve the overall efficiency [8~10]. Hollick [8] laid solar PV panels above a wave board painted with dark-color that could easily to absorb irradiation wavelength. This is the combination of solar photoelectric conversion by PV panel and solar hot water by heat conversion, what we called PV/thermal (or PV/T) system.

Tonui and Tripanagnostopoulos [9] made use of air to cool PV panel and indirectly transferred heat to liquid, constructing a PV/thermal solar energy collector. Kumar and Tiwari [10] set a solar PV panel beside the stored solar water heating tank to form a PV/thermal system and improved the overall efficiency to more than 52%.

This research is to recycle the waste heat from solar PV panel during the photoelectric conversion process. Normal solar hot water absorbs irradiation energy with heat collector, and converses solar energy to heat the water in the sink.

A storage-type solar PV/thermal hybrid system added directly a storage tank below the PV panel directly to cool the surface of PV panel. Solar PV test equipment has constructed to adjust the irradiation amount of halogen light. When the light irradiate on the solar PV panel, voltage and current of PV panel can be measured with I-V curve measurer and drawn an I-V curve to analyze the efficiencies. This experiment was carried out with different irradiation of 600~900W/m^2 and 30∘inclination angel of PV/thermal system to obtain the total efficiency and the surface temperature of the solar PV panel. During the photoelectric conversion process of solar PV panel, the waste heat on the surface will affect conversion efficiency. Total efficiency of a storage-type solar PV/thermal hybrid system combining photovoltaic efficiency of PV panel and hot water efficiency of solar hot water system can be obtained.

2. Methods

Voltage and electric current of PV chip is always tested when absorbing different irradiation to form a I-V curve and get the efficiency. As shown in figure 1, the numbers of voltage and electric current were measured at different loads to form the I-V curve. There are five important parameters in the I-V curve. I_{sc} and V_{oc} are the short-circuit current and open-circuit voltage. The point P_{max} shows the maximum power at the I-V curve, and I_{max} and V_{max} are defined as the electric current and voltage at the P_{max} position.

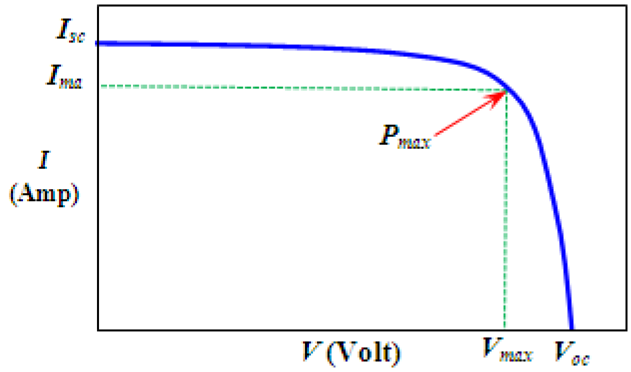


Figure 1. The characteristic curve of solar PV chip

Figure 2 shows the correlation chart between I-V curves with different irradiation amount. I-V curve promotes with increases of irradiation. The short-circuit current I_{sc} and open-circuit voltage V_{oc} are also increase with increases of irradiation. Figure 3 shows the correlation chart between I-V curves and surface temperature at the same irradiation. I-V curve reduces with the increases of surface temperature at the same sunlight amount. Then, conversion efficiency of PV panel reduces also with the increases of surface temperature. It reveals that the efficiency of PV chip is affected obviously by the surface temperature of solar PV.

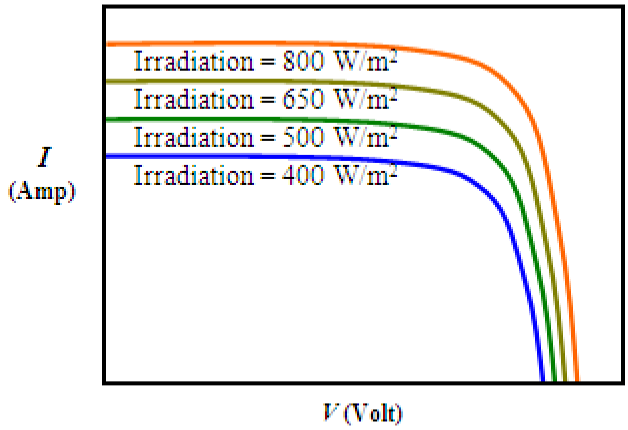


Figure 2. The correlation chart between I-V curves with different irradiation

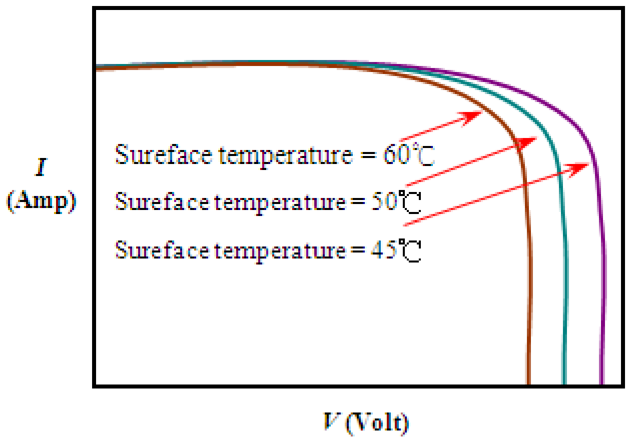


Figure 3. The correlation chart between I-V curves and surface temperature at the same irradiation

The surface heat generated at the irradiating solar PV panel can be cooled; the waste heat can be used to become hot water. It forms the structures of PV/thermal hybrid system. This hybrid system not only can cool the surface of the solar PV panel, but can recycle the waste heat without pump pressurization. The solar energy can be applied effectively.

The experimental data of PV/thermal hybrid system at different irradiation can be measured, including I-V curve, surface temperature distribution of PV panel, and water temperature inside the water tank below the PV panel. Photovoltaic efficiency and hot water efficiency can be calculated by the efficiency equations. Then, the best design parameters to promote the total efficiency of the PV/thermal hybrid system can be got from our experiments.

Several efficiencies in this research can be defined and calculated as follows. Photovoltaic efficiency of the PV panel, η_e, can be defined as:

$$\eta_e = \frac{P_{max}}{I(t) \cdot A_c} \cdot 100\% \quad (2\text{-}1)$$

$I(t)$ is the irradiation amount, and A_c is the surface area of the PV panel. The photovoltaic efficiency is tested and read immediately by the I-V measuring instrument. Hot water efficiency of the solar PV/thermal hybrid system, η_w, can be defined as:

$$\eta_w = \frac{m_w C_w (T_t - T_i)}{\sum [I(t) \cdot \Delta t] \cdot A_c} \cdot 100\% \quad (2\text{-}2)$$

m_w and C_w are the weight and the specific heat of the water in the tank. Δt is the interval of each experiment. T_i and T_t are the average water temperature of the tank before and after each experiment. The total photo-electric conversion efficiency, $\eta_{e,total}$, can be defined as:

$$\eta_{e,total} = \eta_e + \eta_c \cdot \eta_w \quad (2\text{-}3)$$

η_c is the electric/heat energy conversion that is changed into the PV panel electric/heat conversion efficiency. According report to Ji et al. [11] and Huang [12], heat energy has lower conversion energy level than electric energy, and its η_c is about 0.38. Namely, the hot water efficiency is about 38% of the photovoltaic efficiency. That is,

$$\eta_{e,total} = \eta_e + 0.38 \cdot \eta_w \quad (2\text{-}4)$$

The structure of storage-type solar PV/thermal hybrid system is shown in figure 4. Thermal pad is set for conducting the waste heat from the PV panel to storage water tank. Experimental setup shows as figure 5. I-V curve is obtained by solar I-V measuring instrument of accuracy ±1% reading value. Light source of halogen lamp is controlled by the angle inclination adjustment. Thermocouple of accuracy ±0.1℃ and infrared thermal imager of accuracy ±2% are used to measure the water temperature of water tank and the surface temperature of PV panel respectively. Water tank is set below the PV panel to receive the waste heat directly, as shown in figures.

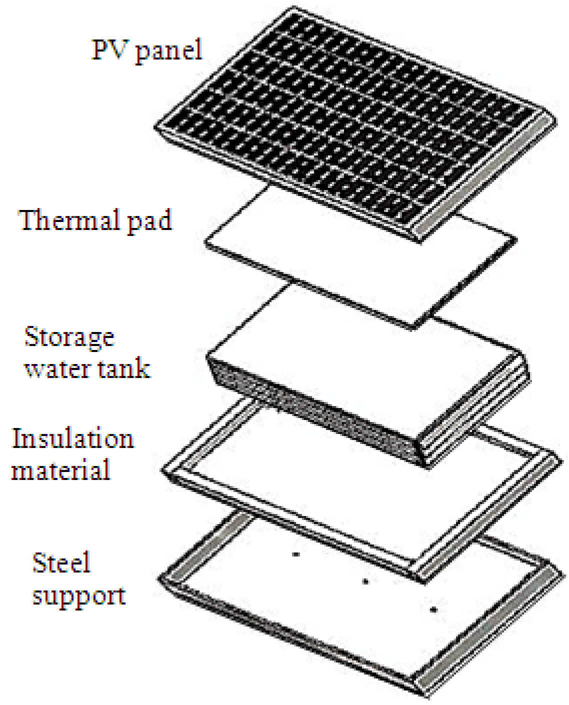


Figure 4. The structure of of storage-type solar PV/thermal hybrid system

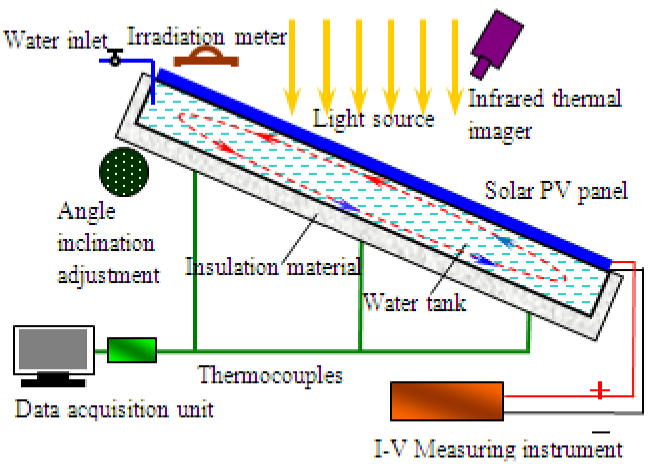


Figure 5. The experimental equipment setup of storage-type solar PV/thermal hybrid system

3. Results

Characteristic analysis of storage-type solar PV/thermal hybrid system

The inclination angel of the solar PV panel is set to be 30°. The irradiation amount of 600, 700, 800 and 900 W/m^2 used halogen light to simulate sunshine can be adjusted by tuner and measured by irradiation meter. Irradiation lighting for 60 minutes each experiment I-V curves, as shown in figure 6, were obtained by I-V measuring instrument at the irradiation adjusted 600~900 W/m^2. Closed-circuit current stably grows with the increase of irradiation amount; however, the open-circuit voltage is hold at a certain extent in spite of the different irradiation. The data of I-V curves show electric current drops to zero dramatically as output voltage is close to the open-circuit voltage at each irradiation amount. Short-circuit current is varied at different irradiation amount from 0.068A to 0.179A. Electric current drops greatly at output voltage about 15V. As output voltage rises to the open-circuit voltage about 19V, electric current drops to 0A.

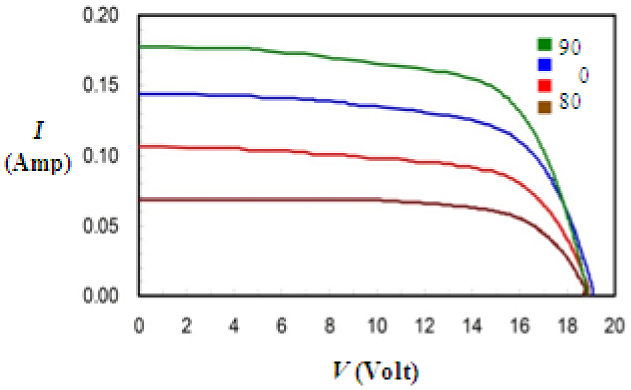


Figure 6. The correlation chart between current and voltage of PV panel of solar PV/thermal hybrid system as irradiation of 600~900 W/m^2

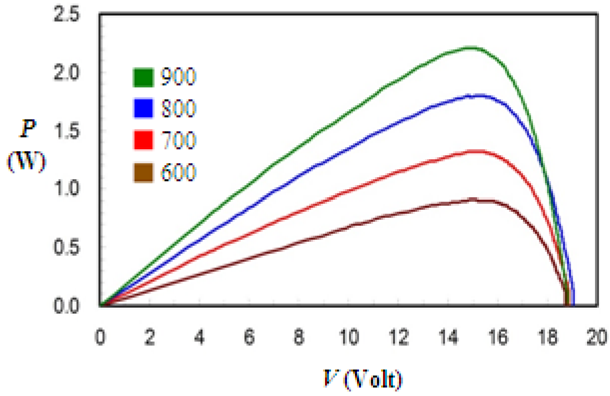
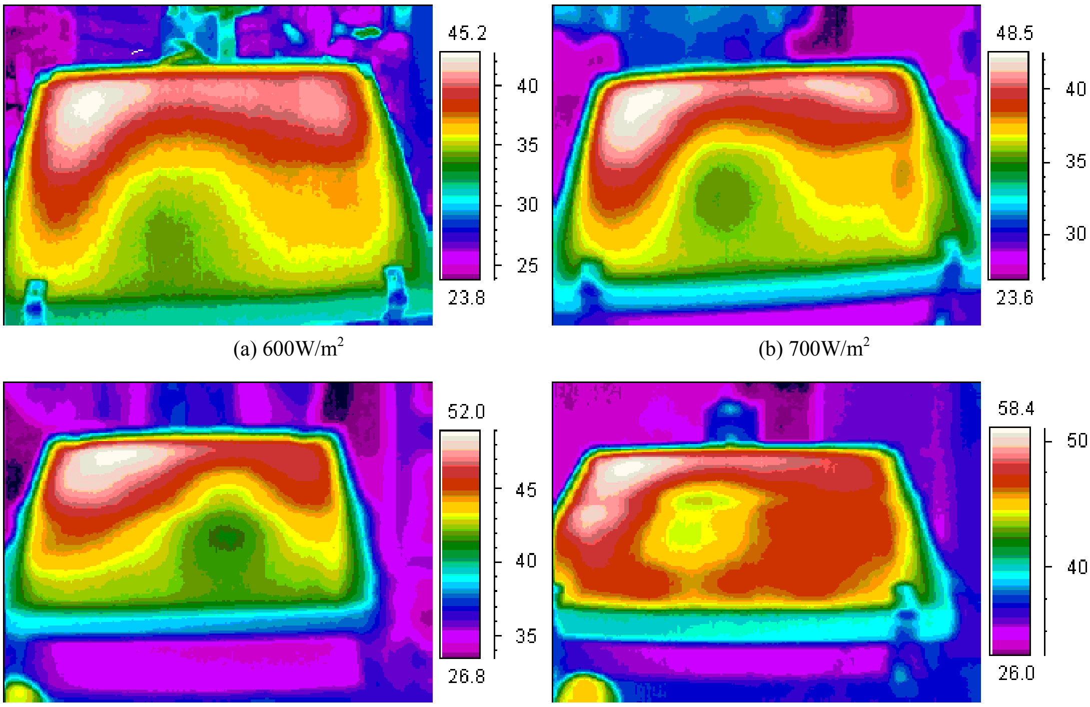


Figure 7. The correlation chart between output power and voltage of PV panel of solar PV/thermal hybrid system as irradiation of 600~900 W/m^2

The correlation between output power and voltage, as shown in figure 7, were obtained also by I-V measuring instrument. Photovoltaic power stably grows with the increase of irradiation amount. The data of P-V curves show photovoltaic power increases to the maximum value and drops to zero dramatically as output voltage is close to the open-circuit voltage at each irradiation amount. The point of maximum power is located at the output voltage about 15V. Maximum power is varied at different irradiation amount from 0.7W to 2.2W.

Surface temperature distribution of PV panel in the storage-type solar PV/thermal hybrid system was imaged by infrared thermal imager. Imaging pictures of surface temperature of PV panel was captured in the last experiment period with different irradiation of 600~900 W/m^2, as shown in figure 8. The highest surface temperature located on the upper surface of the PV panel is 45.2~58.4 °C. As we know, surface temperature of the PV panel is almost about 60~85 °C generally when sun shines outside without cooling PV panel. The temperature of PV panel cooled in the storage-type solar PV/thermal hybrid system decreases very obviously. The result makes sure that photovoltaic efficiency of PV panel can maintain in the storage-type solar PV/thermal hybrid system.



(a) 600W/m^2 (b) 700W/m^2 (c) 800W/m^2 (d) 900W/m^2

Figure 8. Imaging pictures of surface temperature of PV panel with different irradiation of 600~900 W/m^2.

Efficiency analysis of storage-type solar PV/thermal hybrid system

Experiment data of water temperature of storage-type PV/thermal hybrid system is listed in table 1, the interval of each experiment at irradiation lighting is for 60 minutes. The water temperature T_1, T_2 and T_3 are measured by thermocouples respectively on top, middle and bottom of the storage tank. Tavg is the average value of T_1, T_2 and T_3 water temperature. Average water temperatures Tavg increase with the increase of irradiation amount steadily. The data show the water temperature difference (T_t-T_i) increases with the increase of time when halogen light shining on the PV panel. Table 1(a)~(d) also shows the water temperature difference (T_t-T_i) increases with the increase of different irradiation amount.

Photovoltaic efficiency of the PV panel, η_e, is read by measured the I-V curve with solar I-V measuring instrument at different irradiation amount. Hot water efficiency of the solar PV/thermal hybrid system, η_w, is calculated from equation (2-2) by the substitution of water temperature in the tank in table 1. For example, the weight m_w and the specific heat of the water C_w are 1.389 kg and 4200 J/kg respectively. The value (T_t - T_i) from table 1 is 15℃ at the irradiation of 600 W/m^2. The interval of each experiment is 1 hour, and the Δt value is brought 3600s into equation (2-2). The surface area of the PV panel A_c is 1060 cm^2, and the value is brought 0.106 m^2 into equation (2-2). So, the hot water efficiency η_w is can be calculated as 0.3821. Total photo-electric conversion efficiency, η_e, total, can be is calculated from equation (2-3) or (2-4).

The Various efficiency of storage-type PV/thermal hybrid system is listed in table 2. Though, heat energy increases with the increase of irradiation amount, hot water efficiency η_w is maintained about 38~40%. Because of experimental simulated light with halogen lamp in the Lab, pure photovoltaic efficiency ηe is about 5~6%. The electric/heat energy conversion efficiency η_c is 0.38, recycling hot water gets more electric/heat conversion efficiency $\eta_c \cdot \eta_w$ about 14~15%. It reveals that the hot water conversion efficiency of storage-type PV/thermal hybrid system is almost triple than pure solar photovoltaic efficiency. Total efficiency ηe,total calculated is about 19~21%. The results show that total efficiency $\eta_{e,total}$ is almost 4 times as compared to the pure photovoltaic efficiency η_e.

Table 1. Water temperature in the tank of storage-type solar PV/thermal hybrid system

(a) Irradiation 600 W/m^2

Time (min) / Temperature (℃)	0 (T_i)	15	30	45	60 (T_t)	(T_t-T_i)
T_1	27.5	28.3	29.1	34.7	38.7	11.2
T_2	27.1	27.5	31.3	38.5	42.9	15.8
T_3	27.3	31.7	35.1	41.9	45.4	18.1
T_{avg}	27.3	29.1	31.8	38.3	42.3	15.0

(b) Irradiation 700 W/m^2

Time (min) / Temperature (℃)	0 (T_i)	15	30	45	60 (T_t)	(T_t-T_i)
T_1	27.0	27.8	31.4	35.0	40.6	13.6
T_2	26.9	28.7	33.0	39.5	44.8	17.9
T_3	26.8	31.2	40.6	45.0	48.7	21.9
T_{avg}	26.9	29.2	35.0	39.8	44.7	17.8

(c) Irradiation 800 W/m^2

Time (min) / Temperature (℃)	0 (T_i)	15	30	45	60 (T_t)	(T_t-T_i)
T_1	25.8	29.5	32.8	37.8	40.9	15.2
T_2	25.6	31.7	34.1	41.1	45.0	19.4
T_3	25.5	32.3	38.4	47.7	52.9	27.4
T_{avg}	25.6	31.1	35.1	42.2	46.2	20.6

(d) Irradiation 900 W/m^2

Time (min) / Temperature (℃)	0 (T_i)	15	30	45	60 (T_t)	(T_t-T_i)
T_1	26.5	28.2	33.0	38.9	43	16.5
T_2	26.8	32.4	38.8	42.1	47.6	20.8
T_3	26.8	34.6	45.5	49.6	56.0	29.2
T_{avg}	26.7	31.7	39.1	43.5	48.8	22.1

Table 2. Efficiency data of storage-type PV/thermal hybrid system at different irradiation amount

Efficiency (%) / Irradiation (W/m^2)	η_e	η_w	$\eta_c \cdot \eta_w$	$\eta_{e,total}$
600	5.18	38.21	14.51	19.70
700	5.14	38.82	14.75	19.89
800	5.23	39.35	14.95	20.18
900	5.35	39.00	14.82	20.17

4. Conclusions

Storage-type solar PV/thermal hybrid system is set up to cool the surface of PV chip and reuse the waste heat. Surface temperature of PV panel has been cooled decreases obviously as shown with IR thermal imager in the storage-type solar PV/thermal hybrid system. The result makes sure that the photovoltaic efficiency of PV panel can maintain in the storage-type solar PV/thermal hybrid system.

Total efficiency transformed by the photovoltaic efficiency and hot water efficiency. The results show that total efficiency in experiment is more excellent as compared to the pure photovoltaic efficiency. The hot water efficiency of PV/thermal hybrid system from recycling waste heat gets 38~40%, and the electric/heat conversion efficiency gets about 14~15%. In real sunshine surrounding, photovoltaic efficiency of PV chip is about 10~15% at the irradiation of 600~900 W/m^2. It shows, though in real sunshine surrounding, the total efficiency of storage-type PV/thermal hybrid system is more twice than pure solar photovoltaic efficiency.

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