Performance Study of a Hybrid Concentrated Photovoltaic-Methanol Reforming Thermochemical Power Generation System (Postprint)

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Date: 2017-10-17T00:00:00+00:00

Abstract

This paper proposes a power generation system that integrates solar photovoltaic cells with methanol low-to-medium temperature reforming reactions. Through cascade utilization of solar energy and energy grade coupling between physical and chemical energy, the net solar power generation efficiency is significantly enhanced compared to single photovoltaic or methanol thermochemical power generation approaches. Thermodynamic analysis demonstrates that within the system operating temperature range of 100-250°C, the theoretical net solar power generation efficiency of the system reaches 43.6%-44.3% (with optical losses accounted for), markedly surpassing photovoltaic systems (22.5%) and thermochemical systems (32.7%). Approximately 50% of the system' s net solar power generation is derived from hydrogen produced through methanol reforming, achieving efficient solar energy storage in chemical form, while the complementary opposite temperature-dependent trends of photovoltaic and thermochemical power generation produce a stable output. Additionally, approximately 25% of the electricity generated by the system originates from solar energy, exceeding the 14% of single solar methanol thermochemical power generation systems and reducing dependence on fossil fuels. Photovoltaic-thermochemical complementary power generation offers a new approach for the efficient comprehensive utilization of solar energy.

Full Text

Preamble

Performance Analysis of a Hybrid Solar Power Generation System Integrating Concentrated Photovoltaics and Methanol Reforming Thermochemistry

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Abstract: This paper proposes a hybrid solar power generation system that combines solar photovoltaic cells with mid-/low-temperature methanol reforming reactions. Through cascaded utilization of solar energy and coupling of energy grades between physical and chemical energy, the system's net solar-electric efficiency achieves significant improvement compared to photovoltaic-only or methanol thermochemical-only systems. Thermodynamic analysis demonstrates that within the operating temperature range of 100–250°C, the system' s theoretical net solar-electric efficiency reaches 43.6%-44.3% (accounting for optical losses), substantially higher than that of photovoltaic systems (22.5%) and thermochemical systems (32.7%). Approximately 50% of the net solar electricity originates from hydrogen produced via methanol reforming, enabling high-efficiency solar energy storage in chemical form. Moreover, the complementary opposite trends of photovoltaic and thermochemical generation with temperature variation achieve stable output. Additionally, about 25% of the system' s electricity output derives from solar energy, higher than the 14% in solar methanol thermochemical-only systems, thereby reducing dependence on fossil fuels. Photovoltaic-thermochemical complementary power generation provides a new approach for comprehensive and efficient solar energy utilization.

Keywords: solar energy; photovoltaics; solar thermal; thermochemistry; cascade utilization

0 Introduction

Rapid increases in fossil fuel consumption have led to energy shortages, environmental pollution, and climate change. Solar energy, characterized by its vast availability, wide distribution, and clean, low-carbon nature, holds promise for gradually replacing fossil fuels and promoting sustainable development. The International Energy Agency predicted in 2014 [1] that by 2050, solar photovoltaic power generation would account for 16% of global electricity production, while solar thermal power generation would account for a significant portion as well.

Existing solar energy technologies still face limitations of low efficiency, high cost, and unstable energy supply. Photovoltaic power generation efficiency remains relatively low: in single-junction solar cells, low-energy photons below the bandgap cannot be utilized, while high-energy photons above the bandgap lose their excess energy as heat. Consequently, under non-concentrated conditions, the theoretical maximum efficiency of single p-n junction photovoltaic cells is 10%-20% [1]. Multi-junction photovoltaic cells can improve photon energy-bandgap matching by stacking p-n junctions with different bandgaps, achieving theoretical efficiencies of 69% under non-concentrated conditions and 86% at the theoretical maximum concentration ratio (approximately 46,000 suns) [3]. However, constrained by materials, fabrication processes, and costs, the number of p-n junctions is typically limited to four or fewer [4]; the current laboratory record for four-junction photovoltaic cells stands at 46% [4], meaning over half of the solar energy is converted to heat. More importantly, from both efficiency and cost perspectives, multi-junction photovoltaic cells must be paired with concentrators, so the actual power generation efficiency must account for optical losses. With an optical efficiency of 72% and a module-to-cell efficiency ratio of 90%, a photovoltaic cell with a nominal efficiency of 46% achieves an actual power generation efficiency of only 29.8% at room temperature (25°C). Concentration inevitably causes significant temperature rise, further reducing the actual efficiency of photovoltaic cells.

Since photovoltaic cells inevitably convert more than half of solar energy into heat during power generation, recovering and utilizing this thermal energy may improve overall solar energy utilization efficiency. Chubb et al. proposed the concept of combining photovoltaics with heat engines to generate electricity from PV waste heat [5], and numerous researchers have conducted similar studies [6][7]. Kosmadakis analyzed a system combining silicon-based concentrator photovoltaic cells with an organic Rankine cycle, but due to the low efficiencies of both components, the system achieved only modest efficiency improvement (from 9.81% to 11.83%, a mere 2 percentage points) [8]. Tourkov et al. [9] further proposed a system combining triple-junction gallium arsenide photovoltaic cells with an organic Rankine cycle, reporting a theoretical efficiency of 45% without accounting for optical losses. With an optical efficiency of 72%, the system efficiency would be 32%, representing only a 4 percentage point improvement over standalone photovoltaic cells (28%).

The limited efficiency improvement in photovoltaic-heat engine hybrid systems primarily stems from the significant negative temperature coefficient of solar cells and the low efficiency of heat engines at moderate temperatures (e.g., 12.3% at 150°C [10]) that increases only slowly with temperature. In such photovoltaic-thermal systems, the contribution of the heat engine is largely offset by the efficiency decline of the photovoltaic component with rising temperature. Additionally, these systems face challenges of unstable energy supply due to the difficulty of large-scale, long-duration energy storage for both electricity and heat.

In 1980, Professor Wu Zhonghua proposed in a science and technology lecture report for the Central Secretariat of the Communist Party of China that energy sources of different grades should be rationally allocated and supplied according to their appropriate applications, advocating for the development of combined cycles, cogeneration, and waste energy utilization systems based on the principle of "temperature matching and cascade utilization" [11]. Subsequently, Jin Hongguang and colleagues further developed this theory, proposing a theoretical framework for the comprehensive cascade utilization of chemical and physical energy. Based on this theory, they introduced a mid-low temperature solar methanol decomposition power generation system achieving a theoretical net solar-electric efficiency of 35% [12]. In this system, solar thermal energy at approximately 200°C drives the methanol decomposition reaction to produce syngas ($CH\ OH(g) \rightarrow CO(g) + 2H\ (g)$, $\Delta H = 96.79$ kJ/mol). The syngas is then fed into a combined gas-steam cycle, releasing thermal energy at high temperatures (e.g., 1300°C) through combustion. Through this process, low-grade solar thermal energy is first converted to high-grade chemical energy stored in the syngas, and ultimately converted to high-temperature thermal energy during combustion, thereby upgrading the grade of solar thermal energy and achieving high system efficiency. However, in this system' s solar energy absorption and conversion process, high-grade solar radiation is entirely converted to lower-grade thermal energy, resulting in substantial irreversible losses and leaving room for further efficiency improvement.

Based on the theory of comprehensive cascade utilization of energy, the authors previously proposed a solar concentrator photovoltaic and methanol decomposition hybrid power generation system [13]. In this system, solar energy is sequentially utilized by photovoltaic cells and thermochemical reactors, achieving a theoretical net solar-electric efficiency of 43%. However, the methanol decomposition reaction only achieves high conversion rates at temperatures above 200°C (as shown in [Figure 1: see original paper]), which would cause photovoltaic cell efficiency to decline and is unfavorable for long-term operation. In contrast, methanol reforming reactions can achieve desirable conversion rates at 150°C, benefiting photovoltaic cell lifespan, cost, and selection range. This paper proposes a solar photovoltaic-thermochemical hybrid power generation system based on methanol reforming reactions. Using thermodynamic laws, we comparatively analyze the solar power generation efficiencies of standalone photovoltaic systems, standalone solar methanol thermochemical systems, and solar photovoltaic-thermochemical hybrid systems. Specifically, from the perspective of cascade energy utilization, we analyze the reasons for efficiency improvement in the hybrid system and examine its energy storage characteristics and potential for stable power supply.

[Figure 1: see original paper] Comparison of methanol conversion rates between decomposition and reforming reactions of methanol [14]

1 System Description

As shown in [Figure 2: see original paper], the solar photovoltaic-thermochemical hybrid system primarily consists of a solar photovoltaic-thermochemical reaction device, a gas separation unit, and a fuel cell power generation unit. The solar photovoltaic-thermochemical reaction device comprises a point-focus Fresnel lens, concentrator photovoltaic cells, a methanol reforming preheater, and a reactor. In the system, methanol and water are fed into the solar photovoltaic-thermochemical reaction device at a molar ratio of 1:1. Solar radiation is concentrated by the Fresnel lens onto the surface of the concentrator photovoltaic cells, where it is converted into electricity and heat. The electricity is directly output, while the heat serves as the energy source for the methanol reforming preheater and reactor, vaporizing methanol and water and driving the reforming reaction. According to Lin et al. [15], catalysts can control the methanol reforming reaction products to be only CO and H , i.e., only the following reaction occurs: CH OH(g) + H O(g) → CO (g) + 3H (g), ΔH = 56.71 kJ/mol. The higher-temperature products (CO , H) and unreacted reactants (CH OH, H O) at the reactor outlet are used to preheat the incoming reactants. The final products (CO , H) and unreacted reactants (CH OH, H O) are fed into the gas separation unit, where CO and H are separated via membrane separation. The separated CO is captured and recovered, while hydrogen is stored in a hydrogen tank and fed into the fuel cell as needed to generate electricity. The remaining unreacted reactants are recycled.

[Figure 2: see original paper] Schematic diagram of solar photovoltaic and thermochemical hybrid system, including solar photovoltaic and thermochemical reactors, gas separators and fuel cells.

2 System Thermodynamic Performance Simulation

Solar energy concentrated by the concentrator onto the photovoltaic cell surface experiences optical losses during the concentration process. The optical loss energy and the solar energy absorbed by the photovoltaic cell are given by:

$$Q_{\text{opt,loss}} = \text{DNI} \cdot A \cdot (1 - \eta_{\text{opt}})$$

$$Q_{\text{PV,abs}} = \text{DNI} \cdot A \cdot \eta_{\text{opt}}$$

where DNI is the direct normal irradiance, A is the solar concentrator area, and _opt is the optical efficiency, taken as 72%. The photovoltaic cell converts a portion of the absorbed solar energy into electricity and the remainder into heat, expressed as:

$$W_{\text{PV}} = Q_{\text{PV,abs}} \cdot \eta_{\text{PV}}(T)$$

$$Q_{\text{thermal}} = Q_{\text{PV,abs}} \cdot (1 - \eta_{\text{PV}}(T))$$

where _PV(T) is the efficiency of the photovoltaic cell module at temperature T. Based on the temperature range of methanol reforming reactions, this study selects triple-junction gallium arsenide photovoltaic cells with excellent high-temperature performance, which can operate at 250°C for extended periods [16]. The module efficiency expression is [17]:

$$\eta_{\mathrm{PV}}(T) = \eta_{\mathrm{cell}} \cdot C \cdot [1 - 0.0142 \ln(C) - 0.000715(T - 273.15)]$$

where C is the concentration ratio of the point-focus Fresnel lens, taken as 500 in this study. A portion of the solar thermal energy is lost to the environment through radiation and convection:

$$Q_{\mathrm{loss,thermal}} = h \cdot (T - T_0) + \varepsilon\sigma \cdot (T^4 - T_0^4)$$

where h is the convective heat transfer coefficient (10 W/(m² · K)), is the emissivity, is the Stefan-Boltzmann constant, and T is the ambient temperature. The heat absorbed by methanol and water in the preheater and reactor equals the difference between the thermal energy converted by the photovoltaic cell and the heat loss:

$$Q_{\mathrm{reaction}} = Q_{\mathrm{thermal}} - Q_{\mathrm{loss,thermal}}$$

The absorbed heat is used to preheat methanol and water and drive the reforming reaction. The heat requirements for the preheating and reaction processes are simulated in ASPEN Plus [14]. Additionally, the waste heat recovery from reaction products (CO , H) and unreacted reactants is also simulated using ASPEN Plus.

The chemical energy of the reaction product H originates partially from the chemical energy of methanol and partially from solar energy. The solar energy converted to chemical energy is:

$$E_{\text{solar-chem}} = \dot{n}_{\mathrm{H_2}} \cdot \mathrm{HHV}_{\mathrm{H_2}} - \dot{n}_{\mathrm{methanol}} \cdot \mathrm{HHV}_{\mathrm{methanol}}$$

where $\dot{n}$ is the molar flow rate and HHV is the higher heating value. The separated hydrogen is stored in a tank and supplied to the fuel cell as needed. The fuel cell power generation is:

$$W_{\mathrm{FC}} = \dot{n}_{\mathrm{H_2}} \cdot \mathrm{HHV}_{\mathrm{H_2}} \cdot \eta_{\mathrm{FC}}$$

where _FC is the fuel cell efficiency, taken as 50% based on reference [19]. Since a portion of the H chemical energy originates from solar energy, the electricity generated from solar energy in the fuel cell is:

$$W_{\mathrm{solar,FC}} = E_{\text{solar-chem}} \cdot \eta_{\mathrm{FC}}$$

3.1 Complementary System Efficiency Improvement

As a multi-input solar power generation system, the solar photovoltaic-thermochemical hybrid system is evaluated using net solar-electric efficiency, defined as:

$$\eta_{\mathrm{solar}} = \frac{W_{\mathrm{solar}} - W_{\mathrm{pump}}}{\mathrm{DNI} \cdot A}$$

where W_{solar} is the net solar electricity generation and W_{pump} is the power consumption for gas membrane separation. W_{solar} consists of two parts: electricity directly generated by the photovoltaic cell (W_{PV}) and electricity generated by the fuel cell from solar energy ($W_{\mathrm{solar,FC}}$). If the photovoltaic cell efficiency η_{PV} is set to 0, Equation (13) yields the net solar-electric efficiency of a standalone solar methanol thermochemical power generation system.

[Figure 3: see original paper] shows the variation of net solar-electric efficiency with operating temperature for three systems: standalone solar photovoltaic, standalone solar methanol thermochemical, and solar photovoltaic-thermochemical hybrid. Here, "operating temperature" refers to the photovoltaic cell temperature for the PV-only system, and the methanol reforming reaction temperature for the other two systems. The results reveal that the hybrid system' s net solar-electric efficiency initially increases then decreases with rising temperature, but remains more stable compared to the standalone systems. This stability arises because the temperature responses of the PV and thermochemical components are opposite and partially cancel each other out.

Specifically, for the standalone photovoltaic system, the negative temperature coefficient of PV cells causes efficiency to decrease with increasing temperature. At PV cell temperatures of 25°C, 100°C, and 250°C, the PV module efficiencies are 33.5%, 31.3%, and 26.6%, respectively, yielding system power generation efficiencies of 24.2%, 22.5%, and 19.1% (after accounting for Fresnel lens optical losses). For the standalone solar thermochemical system, as the methanol reforming reaction temperature increases from 100°C to 250°C, the net solar-electric efficiency rises from 30.8% to 32.7%. This occurs because, on one hand, the methanol reforming conversion rate increases with temperature, reducing the amount of unreacted reactants to be recycled and associated energy losses, thereby increasing system efficiency. On the other hand, heat losses increase with temperature, reducing efficiency. At lower temperatures, the conversion rate effect dominates, causing efficiency to increase. However, since the methanol reforming conversion rate varies only modestly within the 100–250°C range (as shown in [Figure 1: see original paper]), the thermochemical system efficiency increases only slightly, which benefits the stability of the hybrid system efficiency.

Similarly, in the photovoltaic-thermochemical hybrid system ([Figure 3: see original paper]), as the operating temperature increases from 100°C to 170°C, the

PV component efficiency decreases (22.5% to 21.9%) while the thermochemical component efficiency increases (21.1% to 22.5%). The latter dominates, causing the net solar-electric efficiency to gradually increase (43.6% to 44.3%). As temperature further increases from 170°C to 250°C, the PV component efficiency continues to decline (21.9% to 21.1%), while the thermochemical component efficiency increases but at a slower rate (22.5% to 23.0%). The PV effect then dominates, causing the net solar-electric efficiency to slightly decrease (44.3% to 44.1%). Overall, within the 100-250°C range, the opposite temperature responses of the PV and thermochemical components result in a narrower, more stable system efficiency variation (43.6%-44.3%), compared to 19.1%-25.0% for the PV-only system and 30.8%-32.7% for the thermochemical-only system. Furthermore, since PV cells achieve higher efficiency at lower temperatures, the hybrid system’ s maximum efficiency occurs at a lower temperature than the thermochemical-only system, which benefits system design and operation, particularly by broadening the selection range of PV cells and extending their service life.

Overall, [Figure 3: see original paper] shows that the solar photovoltaic-thermochemical hybrid system achieves a maximum net solar-electric efficiency of 44.3%, representing an 11.6 percentage point improvement over the thermochemical system’ s maximum efficiency of 32.7%, and a 20.1 percentage point improvement over the photovoltaic system’ s efficiency of 24.2% at 25°C. The efficiency gain over the thermochemical system primarily results from cascaded solar energy utilization (PV followed by thermochemistry). The improvement over the PV system mainly arises from the upgrading of solar thermal energy (physical energy) to higher-grade chemical energy (hydrogen) through coupling with methanol chemical energy. The hybrid system’ s high overall efficiency stems from the synergy between cascaded solar energy utilization and the grade coupling of physical and chemical energy.

The cascaded utilization is achieved by introducing PV cells into the solar absorption and conversion process of the thermochemical system. With PV cells, high-grade solar radiation is first partially converted to electricity. Compared to the thermochemical-only system, the proportion of solar energy directly converted to low-grade thermal energy (around 200°C) is reduced, decreasing irreversible losses in the solar absorption and conversion process and increasing the exergy obtained. To quantitatively analyze the impact of cascaded utilization on exergy gain, we define the exergy obtained per unit of solar energy during the solar absorption and conversion process for both the thermochemical-only system and the hybrid system:

$$\varepsilon_{\text{TC-only}} = \frac{E_{\text{thermal}}}{\text{DNI} \cdot A_{\text{TC-only}}}$$

$$\varepsilon_{\text{hybrid}} = \frac{E_{\text{thermal}} + W_{\text{PV}}}{\text{DNI} \cdot A_{\text{hybrid}}}$$

where $A_{\text{TC-only}}$ is the concentrator area of the thermochemical-only system. The ratio of exergy increase in the hybrid system relative to the thermochemical-only system is defined as:

$$\Delta\varepsilon_{\text{abs}} = \frac{\varepsilon_{\text{hybrid}} - \varepsilon_{\text{TC-only}}}{\varepsilon_{\text{TC-only}}}$$

As shown in [Figure 4: see original paper], the photovoltaic-thermochemical hybrid system obtains more exergy than the thermochemical-only system during solar absorption and conversion. The exergy increase ratio rises monotonically with decreasing reaction temperature, reaching 125% at 100°C (further temperature reduction would yield even higher ratios, though this study is limited to 100–250°C). This indicates that by adding PV cells, the hybrid system obtains more than double the exergy of the thermochemical-only system. The exergy increase ratio gradually declines with rising temperature, dropping to 69% at 250°C. This occurs because at lower temperatures, the thermochemical-only system obtains thermal energy of lower grade and thus less exergy, leaving greater room for improvement. Additionally, PV cells achieve higher efficiency at lower temperatures, generating more electricity and reducing the proportion of solar energy converted to low-grade thermal energy, resulting in greater exergy enhancement at lower temperatures.

[Figure 4: see original paper] Exergy obtained during solar energy absorption and conversion in the thermochemical-only system and solar PV thermochemical hybrid system

The coupling of physical and chemical energy grades refers to the process where solar thermal energy (physical energy) produced by PV conversion is upgraded to higher-grade chemical energy (hydrogen) through the methanol reforming reaction at the cost of reducing methanol' s chemical grade. This solar energy can be stored stably for extended periods and converted to electricity on demand. To analyze the impact of this grade coupling on system efficiency, we select direct solar thermal energy conversion via heat engine as a reference. The electricity converted per unit of solar energy in a heat engine is defined as:

$$\eta_{\text{heat engine}} = \eta_{\text{Carnot}} \cdot \alpha$$

where is the thermodynamic perfection factor, taken as 0.6 [17]. In the hybrid system, the electricity converted per unit of solar energy in the thermochemical component is:

$$\eta_{\text{thermochemical}} = \frac{W_{\text{solar,FC}}}{\text{DNI} \cdot A_{\text{hybrid}}}$$

The ratio of electricity increase from thermal utilization resulting from physical-chemical energy grade coupling is defined as:

$$\Delta\eta_{\text{coupling}} = \frac{\eta_{\text{thermochemical}} - \eta_{\text{heat engine}}}{\eta_{\text{heat engine}}}$$

As shown in [Figure 5: see original paper], as the operating temperature increases from 100°C to 250°C, the electricity generated from solar thermal energy via heat engine utilization continuously increases (from 5.5% to 8.1% of solar input energy), primarily because higher temperatures yield higher-grade thermal energy and thus more electricity conversion. Simultaneously, the electricity generated from solar thermal energy via thermochemical utilization also increases with temperature, due to rising reaction conversion rates (as shown in [Figure 1: see original paper]) and reduced losses in the unreacted reactant recycling process. Comparison reveals that thermochemical utilization of solar thermal energy produces more electricity than heat engine utilization, with an improvement ratio of 164%-281%. This is mainly because, on one hand, the low grade of solar thermal energy limits direct conversion efficiency via heat engines by Carnot efficiency (offering large improvement potential). On the other hand, at the cost of reducing methanol’ s chemical grade, solar thermal energy is upgraded to higher-grade chemical energy through methanol reforming, making the power generation efficiency no longer constrained by the low grade of thermal energy.

[Figure 5: see original paper] Increase of electricity from solar thermal energy resulting from coupling between physical energy and chemical energy

3.2 Complementary System Energy Share

Beyond efficiency advantages, the energy storage capability of the thermochemical component compensates for the storage disadvantage of the PV component, enhancing system power generation stability and continuity. As shown in [Figure 6: see original paper], solar-generated electricity originates from two sources: electricity directly generated by photovoltaic cells and electricity converted from solar thermal energy absorbed by the thermochemical component. Analysis indicates the ratio between these two electricity sources is approximately 1:1, meaning about 50% of net solar electricity can be converted from hydrogen (the thermochemical product) chemical energy. Based on this, the hydrogen supply rate can be adjusted in real-time according to solar irradiance variations, enabling the fuel cell’ s electricity output to perform peak shaving and valley filling for the photovoltaic cell’s electricity output, thereby stabilizing the overall system’ s electricity output.

[Figure 6: see original paper] Shares of different sources of electricity in the solar PV thermochemistry hybrid system

On the other hand, the net solar electricity generation accounts for approximately 25% of the system’ s total electricity output, compared to only 14% in the thermochemical-only system. This is primarily because the introduction of photovoltaic cells increases solar energy utilization and raises the share of net solar electricity. As operating temperature increases, the proportion of net solar electricity in total system output slightly decreases from 25.9% to 24.8%. This occurs because for each unit of solar energy input, as operating temperature rises, the thermal energy provided by PV cells to the thermochemical reaction increases (while PV electricity generation decreases), driving more methanol reforming and gradually increasing the share of electricity from methanol while decreasing the share of net solar electricity.

4 Conclusions

Based on the concept of cascade energy utilization, this paper proposes a solar concentrator photovoltaic and methanol reforming thermochemical hybrid power generation system. The system offers advantages of high solar power generation efficiency, large energy storage proportion, stable power supply, and low fossil fuel ratio. Through cascaded solar energy utilization and grade coupling between physical and chemical energy, the system achieves a theoretical net solar-electric efficiency of 44.3% at an operating temperature of 170°C, surpassing both the thermochemical-only system (32.7%) and the concentrator photovoltaic-only system (24.2%). Approximately 50% of the net solar electricity originates from hydrogen produced via methanol reforming, achieving high-proportion solar energy storage through chemical pathways. The system can regulate solar fuel (hydrogen from methanol reforming) flow to perform peak shaving and valley filling for PV output, improving solar power supply stability. Compared to the standalone solar methanol thermochemical system, the proposed hybrid system increases overall solar power generation efficiency and reduces fossil fuel proportion and dependence. The solar photovoltaic-thermochemical hybrid system presented in this paper provides new insights for solar energy technology development.

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