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RESEARCH ARTICLE OPEN ACCESS

Efficient energy management system for solar energy

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ABSTRACT

To achieve a clean energy carrier, solar energy is expected to play a significant part in the world's future energy situation. Hydrogen is a clean energy source that may be used to Putting an end to global warming by reducing CO2 emissions and replacing fossil fuels. Producing hydrogen from plentiful water and renewable solar energy offers a low-impact way to meet rising global energy needs and provide reliable power for the future. This research zeroes in on photovoltaic-based hydrogen production, with an emphasis on the concentrated photovoltaic (CPV) system, as well as other methods of producing hydrogen from the sun, including solar thermolysis, solar thermal hydrogen via electrolysis, thermochemical water splitting, decarbonization of fossil fuels, and more. Hydrogen generation from CPVs is analyzed thermodynamically, and an energy management system is created as a long-term, low-cost alternative. Alkaline water electrolysis (AWE), polymer electrolyte membrane electrolysis, and solid oxide electrolysis are examined in terms of their potential for connection to solar systems for H2 generation. Given the wide variety of technology used to produce solar hydrogen, the associated difficulties, benefits, and drawbacks, as well as the commercialization processes, are discussed. To connect with the CPV system, AWE is the most developed of the three electrolysis technologies studied for the hypothetical solar hydrogen economy. Solar hydrogen generation technologies have come a long way, but this assessment shows that they still need time to mature before they can effectively replace hydrogen from the grid.

Keywords: electrical power, electrolysis, hydrogen, photovoltaic, solar energy

I. INTRODUCTION

There is a clear lack of environmental, economic, and social sustainability in the current trends in energy consumption and supply. A cariogenic greenhouse gas (GHG) emissions are projected to more than quadruple by 2050 if no action is taken to slow the rising pace of fossil fuel utilization and protect energy storage facilities.1 Obviously, we need to take a turn for the better, and that means exploring options like carbon capture and storage (CCS) and expanding the use of renewable, sustainable energy. For governments and businesses to take the necessary steps towards adopting renewable energy sources, a clear plan of action is necessary. Hydrogen fuel is a sustainable energy carrier that will unavoidably contribute to the global energy situation and aid in the reduction of carbon emissions from the transportation and industrial sectors. Hydrogen fuel is scarce in the free state and is often manufactured in factories. Hydrogen extraction from fuels nowadays often results in significant CO2 emission. Hydrogen may be produced through electrolysis, a method that uses electricity to split water into hydrogen (a clean energy carrier) and oxygen (a harmless byproduct). Hydrogen, like petrol, is a highly combustible fuel, but its buoyancy (14.4 times lighter than air) causes the flame to fly upwards, rather than outwards.

Hydrogen is a flexible fuel used in many ways across all energy sectors. It may be produced using a broad variety of resources. Hydrogen may be classified as "grey hydrogen" (hydrogen from NG without carbon sequestration), "blue hydrogen" (hydrogen from NG with CCS), and "green hydrogen" (hydrogen from renewable energy without causing carbon emissions). Since the cost of NG is the primary factor, grey hydrogen is less expensive than blue and green varieties. The cost of CCS is significant, but the price of NG also influences the blue hydrogen pricing.8 Several variables affect how much eco-friendly hydrogen costs. The cost of green hydrogen should be compared to the cost of the green electricity (electricity produced from renewable and sustainable energy) used in the electrolysis. The expense of electrolysis, the process used to extract hydrogen from water, must also be considered. The price of renewable energy has dropped dramatically in recent years and is expected to drop much more soon. As a result, the possibility of producing environmentally friendly hydrogen for use in vehicles and homes is becoming more likely.10 Hydrogen is generated mostly from fossil fuels, with just around 5% coming from water electrolysis. Green hydrogen has the potential to significantly reduce reliance on fossil fuels if the technological hurdles preventing its widespread production in the United States can be overcome. As a bridge between energy demand and supply, hydrogen may improve the adaptability of low-carbon energy systems in both distributed and centralized settings.

The adoption of hydrogen production technologies, its transmission and distribution, and retail infrastructure are hard, despite the fuel's potential environmental and energy security in end use application.13 To meet the high energy demands of an industrialized society, solar hydrogen production relies on knowledge about the solar power generating technology used. Therefore, the purpose of this article is to investigate current methods for safely producing hydrogen from the sun. In conclusion, this paper's original contributions to the field include a discussion of potential near-term approaches to solar hydrogen generation and thermodynamic evaluations of concentrated photovoltaic (CPV) and electrolysis systems for solar hydrogen production.

II. SOLAR HYDROGEN ENERGY CARRIER

When compared to solar thermal, geothermal, wind, and biomass, solar has the most potential to create low-cost electrical power among the renewables. Solar energy has the greatest potential to meet global energy needs and create a sustainable future. Coal has replaced natural gas and oil as the primary fuel for electricity generation because of their volatile costs ($7.5/million Btu and $55-$110/bbl, respectively) in recent years.

Even though "hydrogen, fuel of the future" is debatable due to hydrogen's drawbacks, such as its low energy content per volume, its high price, the cost of infrastructure, and the high rates of GHG emissions during its production, the decreasing cost of solar electricity holds great promise for the growth of hydrogen production. Solar hydrogen is a clean alternative fuel that can replace fossil fuels and end our reliance on oil and gaseous fuels, reducing our carbon footprint and preventing catastrophic global warming. Since solar energy is abundant and free worldwide, it may be utilized to generate the power necessary for the electrolysis process. The incident solar energy received by Earth's surface each year is around 3.9 1024 MJ, which is almost 10,000 times greater than the current global energy consumption.

If just 1% of this energy could be harnessed, all of humanity's energy needs could be met. It is well acknowledged that solar can satisfy the needs for both large-scale generating and small-scale electricity delivery. Erelong solar will decentralize electrical power production in the same way as telecommunications and computing have in recent decades. When the price of solar power catches up to that of fossil fuel-based energy, and when distributed solar electricity is accepted at the same rate as mobile phones, this massive revolution will be carried out in practice.

Photovoltaic systems, which turn sunshine into electricity without utilizing any intermediate components, are the most efficient and cost-effective way to harness solar energy. The quickest and easiest way to use the sun's energy is made ready by solar cell systems. Due to solar power's potential to meet a large portion of the world's future energy needs, it's important to find cost-effective ways to store the sun's energy so it can be used when it's needed without interruption. When residential rooftop solar systems produce more energy than is needed, the extra power is either stored in batteries (for off-grid systems) or fed into the grid (for on-grid systems), with the homeowner being compensated for the electricity they use. Due to their limited storage capacity and short lifespan, conventional batteries are not a viable solution for long-term energy storage. Hydrogen storage, as opposed to the more conventional battery storage, is a more dependable and efficient option for storing renewable energy. Hydrogen can be produced from excess energy and used as a battery to provide electricity when the sun isn't shining if the cost of fuel cells can be reduced. However, solar energy's intermittent nature necessitates a significant reserve of electrical power be stored for use in restoring electric grid stability. Using solar hydrogen as a potential solution by connecting the solar system to electrolysis is an attractive prospect. Hydrogen produced from the sun has several potential applications; it may be used in homes and businesses, in cars, and in power plants (through fuel cells or direct combustion, with just water as a byproduct).

The current electrolyzes on the market are rather pricey. Still, it's a fantastic concept to utilize the surplus power from rooftop PV systems to split water molecules into oxygen and hydrogen for later use in a fuel cell. When generating electricity from hydrogen and oxygen in a fuel cell, water is created that may be recovered and reused in a closed-loop system. It is inevitable that soon, distributed electricity generation will replace large, centralized fossil fuel power plants and national electric grids, even though the current threshold costs of fossil fuel-based hydrogen and electrolysis hydrogen are approximately $2.00 to $4.00 and $3.26 to $6.62 per gallon of petrol equivalent, respectively. The efficiency of a solar-to-hydrogen system's conversion process is the single most telling measure of its overall effectiveness. Research indicates that the efficiency of solar hydrogen synthesis in a PV-based plant might be boosted by as much as 12%.33 Hydrogen generation based on CPV was claimed to have efficiencies of 18%, 22%, and 24.8% under different circumstances. At a certain amount of direct normal irradiance (DNI), when the maximum power of PV and the IV of the electrolyze are matched, the solar to hydrogen efficiency is maximized. The DNI, cell temperature, and PV maximum power of a genuine solar hydrogen production plant all fluctuate during the day, influencing the plant's performance. Homogeneous charge compression ignition is one method suggested to generate electricity locally using solar hydrogen, which would reduce the expenses of storing and transporting the fuel.

III. CONCENTRATED SOLAR THERMAL HYDROGEN PRODUCTION

shows that thermolysis, electrolysis, and solar titration all use water as their chemical supply of hydrogen.

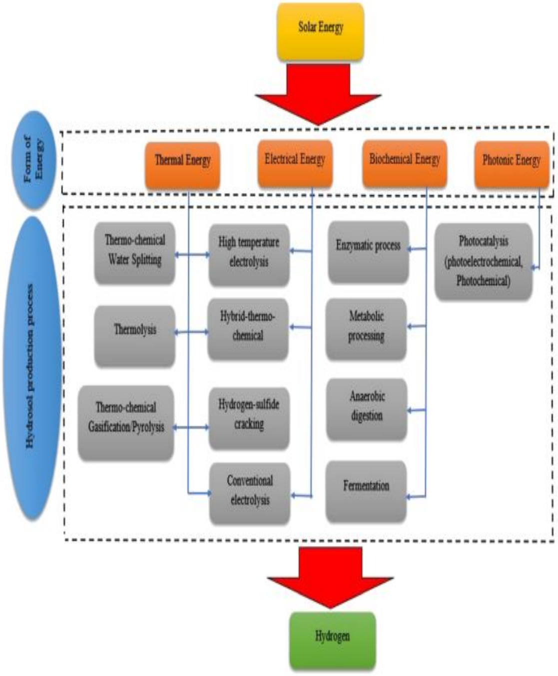
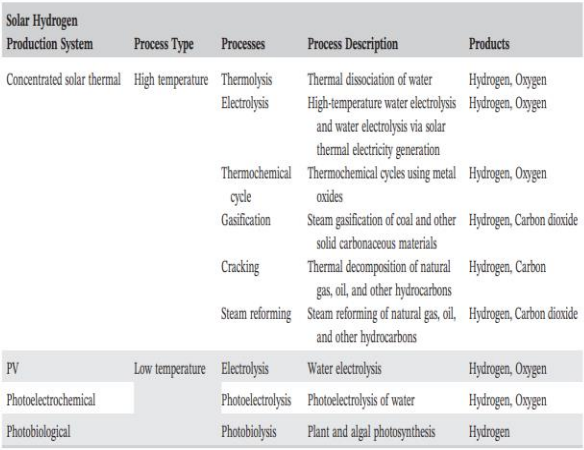


Figure No. 1: Various routes of solar hydrogen production



Solar Hydrogen Production System	Process Type	Processes	Process Description	Products
Concentrated solar thermal	High temperature	Thermolysis	Thermal dissociation of water	Hydrogen, Oxygen
		Electrolysis	High-temperature water electrolysis and water electrolysis via solar thermal electricity generation	Hydrogen, Oxygen
		Thermochemical cycle	Thermochemical cycles using metal oxides	Hydrogen, Oxygen
		Gasification	Steam gasification of coal and other solid carbonaceous materials	Hydrogen, Carbon dioxide
		Cracking	Thermal decomposition of natural gas, oil, and other hydrocarbons	Hydrogen, Carbon
		Steam reforming	Steam reforming of natural gas, oil, and other hydrocarbons	Hydrogen, Carbon dioxide
PV	Low temperature	Electrolysis	Water electrolysis	Hydrogen, Oxygen
Photoelectrochemical		Photoelectrolysis	Photoelectrolysis of water	Hydrogen, Oxygen
Photobiological		Photobiolysis	Plant and algal photosynthesis	Hydrogen

Table No.1 : Options for large-scale solar hydrogen generation in the near future were discussed further, including their various forms, outputs, and methods. sun cracking, solar gasification, and solar steam reforming all need fossil fuels, whereas the thermochemical cycle processes use a mix of fossil fuels and water. The endothermic processes employed in these hydrogen generation systems need the thermal energy from CSP to sustain the high-temperature process. Methods using focused heat energy from the sun to produce hydrogen are outlined below.

3.1: Hydrogen Production via solar process

Water thermal dissociation ($H_2O -> H_2 + \frac{1}{2}O_2$) requires a high temperature (more than 2900 K) to get a sufficient level of dissociation (35% or so). This is one of the major limitations of the method that has slowed its widespread adoption. A significant amount of reradiation from the reactor might reduce the absorption efficiency, adding to the list of material issues for this high-temperature process. Additionally, an efficient mechanism is needed to separate the created H2 and O2 to prevent explosion. H2 and O2 may be separated by electrolytic separation or effusion separation.

Hydrogen generation by the solar thermolysis process has been studied extensively in the 1970s and 1980s, but it has gotten little attention for practical solar hydrogen production due to the scarcity of materials that can withstand such high temperatures. To produce hydrogen, Baykara conducted experiments with a 1 kWth horizontal solar reactor (a zirconia cylinder cavity insulated by porous ceramic; see Figure 2). To evaporate the water before it entered the reactor's cavity, it was piped to the reactor's wall. To channel quenching steam into the reaction zone, four perpendicular jets were built at the front of the reactor. At 2500 and 1500 degrees Celsius, the system's efficiency was determined to be 1.1%, with hydrogen mole fractions achieved of 0.03 and 0.00012, respectively.

3.2: Solar hydrogen synthesis by thermochemical water splitting

Thermochemical solar-to-hydrogen method offers an advantage over thermolysis because to the low temperatures required (about 1200 K) and the elimination of the need for O2/H2 separation. Thermochemical two-step process involving redox reactions in metal oxides:

$$M_xO_y \rightarrow xM + \frac{Y}{2}O_2$$

$$xM + yH_2O \rightarrow M_xO_y + yH_2$$

Metals are denoted by M, and their equivalent oxides by MxOy.

Endothermic solar thermal dissociation of MxOy to the metal or the lower valence metal oxide happened first (solar-based process). The metal is hydrolyzed into hydrogen and the equivalent metal oxide in an exothermic, nonsolar-based process. Therefore, the thermochemical process is a cycle, with the initial components (MxOy) being regenerated and used again in Equation (2). There was no need for a gas separation procedure since hydrogen and oxygen were produced in two distinct ways. Hydrogen generated in this cycle is so clean that it may be used in PEM fuel cells without any further purification steps.

Two revolving fixed beds, a recuperator, a reactor, and a receiver made of ferritereactant material that moves in opposing directions were presented by Driver et al. Solar energy was focused at the top and sent forward of the spinning rings. The sensible heat was recovered via the intermediate rings, and the hydrolysis reaction was carried out. The observed thermal efficiency and hydrogen generation rate were 32.2% and 0.0412 mol/s for 15 kW of incident solar power, respectively.

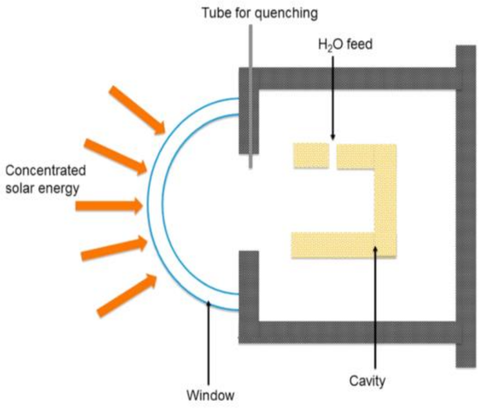


Figure No. 2: Hydrogen manufacturing scheme based on a solar reactor's thermolysis process.

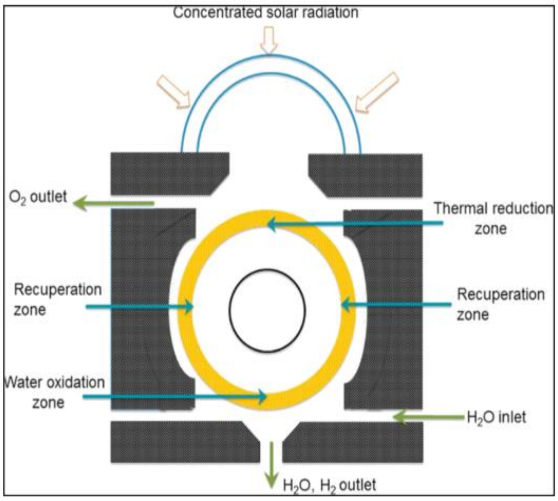


Figure No. 3: Hydrogen is produced in a thermochemical solar reactor, as seen in this diagram.

Thermochemical cycles are classified into volatile and nonvolatile cycles depending on the metal oxide phase in the process, and the solar system is designed accordingly. In a nonvolatile cycle, the reduced oxide never changes state and stays in the solid state, therefore there's no need for a quenching apparatus. However, in volatile redox pairs, the reduced metal oxide undergoes a solid to gas phase shift, which must be considered in the design of the system. Solar dissociation of compressed ZnO and SnO2 powders, to create Zn or SnO, was investigated by Chambon et al. using a 1 kW solar system. By placing a piston at the base of the reactor, we were able to continuously inject reactant in the form of an oxide rod. Thermochemical cycle efficiency was calculated to be between 1% and 3%.

Possible thermochemical cycles that have recently been examined include those with magnesium and chlorine (MgCl), copper and chlorine (Cu Cl), hybrid sulfur (HyS), and sulfur and iodine (SI). Due to its manageable reactions and modest maximum temperature, the MgCl cycle has been presented as a practical thermochemical water splitting technique for solar-to-hydrogen conversion.61 The MgCl2 is hydrolyzed, MgO is chlorinated, and HCl is electrolyzed; these are the three main processes in the MgCl cycle. The four-step MgCl cycle suggested by Ozcan and Dincer63 is compatible with the standard water electrolysis technique, making it more practical and decreasing the necessary electrical effort for the cycle. CuCl, with its mild maximum temperature requirement, is the most plausible approach for solar to hydrogen process that has been established on a global scale.64 To investigate the feasibility of solar hydrogen generation utilizing a heliostat field paired with a CuCl cycle, a team of scientists from the United States, Canada, Romania, Slovenia, and China conducted a case study.65 About 785 MW was received by the solar facility, but only 309 MW were used to heat the molten salt. The plant's efficiency was calculated to be 20%, and the rate at which hydrogen was produced was 0.89-kilogram H_2 per second.

HyS utilizes both thermochemical and electrochemical processes to produce hydrogen. In the endothermic thermochemical phase, high temperatures (about 800°C) and a catalyst are needed. This procedure consumes around one-third of the power required for electrolysis. All reactions in the SI cycle are carried out in the gas or liquid state to reduce the amount of electricity needed for transit. The first part of this cycle involves the decomposition of sulfuric acid over a catalytic bed at high temperatures, resulting in the formation of aqueous sulfur dioxide and oxygen. Second, hydriodic acids of varying gravimetric characteristics and sulfuric are produced when aqueous SO_2 combines with iodine. Sulfuric acid is recycled into the decomposition reactor after being used to degrade hydriodic acid at temperatures between 573 and 623 K, producing hydrogen and iodine. To make up for heat loss, the S-I cycle is heated to a comfortable 950 degrees Celsius.

IV. PV-based Hydrogen Production

One of the most cost-effective methods of converting solar energy into hydrogen is to use a photovoltaic (PV) system to generate electricity and pair it with a low temperature electrolyze. It wasn't until the early 1970s that hydrogen was first produced utilizing a PV system in tandem with water electrolysis. Using a PV current source to directly convert solar power into electricity might be the most cost-effective technique of producing solar hydrogen, especially when environmental and economic impacts are considered. Solar PV cells and the notion of utilizing hydrogen as a clean fuel to replace liquid and gaseous fossil fuels were created by Lodhi.

Using conservative estimates of 20% for PV cell efficiency and 80% for the electrolyzing system, a solar hydrogen production plant's efficiency82 would be about 16%. The poor efficiency of the photovoltaic system is to blame for the low exergy and energy efficiency of a PV-based solar-to-hydrogen unit, as calculated by Joshi et al.84 According to Tributsch85, the efficiency of the solar-to-hydrogen process will be about 8% to 14% for commercial silicon-based PVs if the electrolier's efficiency is 70% to 75%. Commercialization of solar-to-hydrogen systems faces significant challenges due to the poor efficiency of solar hydrogen synthesis. While PV-based hydrogen generation isn't exactly cheap, it's a green technology that doesn't contribute to global warming or cause noise pollution while in use, and it's easy to keep up with since it has no moving parts and requires no maintenance.

Kothari et al.87 noted that using PV cells and electrolysis might increase the efficiency of the solar hydrogen manufacturing process by 25% to 30%. Ulleberg et al.'s 88 research on solar-to-hydrogen systems' efficacy in cold, low-sun environments led them to conclude that, under these conditions, solar hydrogen production systems needed to be relatively big. High temperatures reduce the efficiency of PV systems; to maximize system performance, the PV heat should be directed toward an electrolyze.

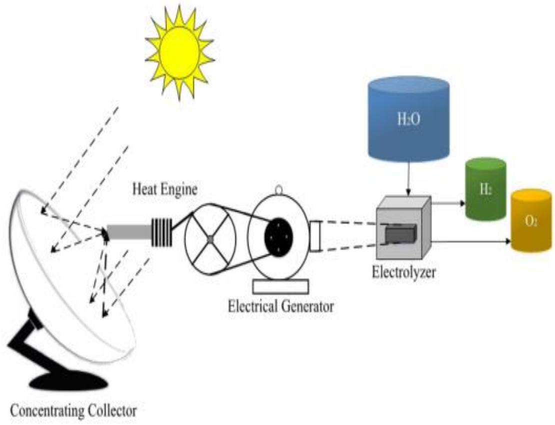


Figure No. 4 : Illustration of the solar thermal hydrogen production system

PVs are constructed from semiconductors, and when exposed to sunlight, these materials produce electron-hole pairs that are kept apart by the electric field inside the junction. There are three generations of PVs based on the semiconductor material they use. Eighty-five percent of the PV market is now supplied by silicon-based PV, which is the first generation of PVs. Multi crystalline PV cells have an efficiency of 20.4%, whereas single crystalline PV cells have an efficiency of 25.6%. Thin-film semiconductors, used in the production of the second generation of PV cells, are widely regarded as the most cost-effective production process currently available. Copper indium gallium selenide solar cells have an energy conversion efficiency of roughly 20.5%, whereas cadmium telluride thin film photovoltaics achieve just 19.6%. The first PV generation's efficiency stems from its reliance on a single junction of semiconductor material to convert a fraction of the sun's rays into electricity while rejecting the rest as heat.90 Solar cells should be able to absorb light throughout a broader range of the solar spectrum to achieve greater efficiency in PV systems. Thus, the third generation of photovoltaics offered technologies like the multijunction solar cell (MJSC), hot carrier solar cell, multiband and thermos PVs, the Gratzel solar cell, and the organic poly merbased solar cell. A broad range of the solar spectrum is absorbed by the PV cells since MJSCs are a mixture of single junction PV cells, each of which functions at a particular section of the spectrum. Large band gap differences result in large solar spectrum losses and convert solar energy to heat, therefore minimizing them is key to maximizing efficiency and minimizing solar energy waste. Almost the full sun spectrum can be converted into power with MJSCs, making them the most efficient solar photovoltaic cells.34 The maximum efficiency of a four-junction photovoltaic (PV) cell is about 64% at one sun and 81% at 10,000 suns.

V. CONCLUSION

There are several advantages to using solar hydrogen as a clean energy carrier since it is produced from a renewable energy source. The intermittent nature of solar energy is a drawback of this clean energy source that may be mitigated by switching to solar hydrogen from conventional batteries. Producing, disposing, and using solar hydrogen via environmentally friendly procedures has far-reaching consequences for sustainable development; it not only helps to fulfill the rising energy needs of the globe but also has a major impact on mitigating climate change. Solar energy conversion costs account for almost all the total cost of producing solar hydrogen. Solar hydrogen generation costs are sensitive to both DNI and solar percentage, with higher costs associated with low DNI and higher solar fraction. Solar-to-hydrogen commercialization relies heavily on accessible, reliable technology.

To improve solar-to-hydrogen through a strong CPV system, as shown in the current review, a connection between mechanical, chemical, and material studies as well as commercial implementation is necessary. More research into semiconductor materials is needed to increase their narrow bandgap to absorb a wider spectrum of solar irradiance, which would improve the performance of solar-to-hydrogen devices. For large-scale, cost-effective solar hydrogen generation soon, AWE is the electrolysis technology that shows the greatest promise.

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