Solar water splitting: efficiency discussion

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Abstract

The current state of the art in direct water splitting in photo-electrochemical cells (PECs) is presented together with: (i) a case study of water splitting using a simple solar cell with the most efficient water splitting electrodes and (ii) a detailed mechanism analysis. Detailed analysis of energy balance and efficiency of solar hydrogen production are presented. The role of hydrogen peroxide formation as an intermediate in oxygen evolution reaction is newly revealed and explains why an oxygen evolution is not taking place at the thermodynamically expected 1.23 V potential.

Solar hydrogen production with electrical-to-hydrogen conversion efficiency of 52% is demonstrated using a simple ∼0.7%-efficient n-Si/Ni Schottky solar cell connected to a water electrolysis cell. This case study shows that separation of the processes of solar harvesting and electrolysis avoids photo-electrode corrosion and utilizes optimal electrodes for hydrogen and oxygen evolution reactions and achieves ∼10% efficiency in light-to-hydrogen conversion with a standard 18% efficient household roof Si-solar cells.

Keywords: solar hydrogen, conversion efficiency, solar-to-hydrogen conversion, oxygen and hydrogen evolution mechanisms

1. Review: materials and cell configurations

A solar water splitting is decomposition of H₂O molecules into molecular hydrogen and oxygen using solar energy. This process is expected to become foundation of a sustainable hydrogen-based energy economy, as it represents carbon-neutral way to produce hydrogen gas using the most abundant renewable resources, i.e., water and sunlight [1 2 3].

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1.1. Early days of solar water splitting

From the technical point of view, there are may ways to realize water splitting, however, the technology must be efficient and economically viable. Comprehensive review, dedicated to the problems of electrolysis of water on light-sensitive semiconductor surfaces [1] covers the period between 1972, when the photoelectrochemical (PEC) water splitting was first discovered [3] and 2010. The authors survey the data related to thermodynamics of hydrogen and oxygen evolution reactions (HER and HOR), performance of various semiconductors, configurations of photoelectrochemical cells, properties of catalyst materials, influence of various structural effects on the efficiency of the process. Values of the energy conversion efficiency or the so-called solar-to-hydrogen efficiency, $\eta_{\text{STH}}$, obtained for water splitting cells of different configurations are summarized [1]. The values vary between 0.01% and 18%, i.e., by a factor of about 2000, for PEC cells without surface catalysts and those with catalysts and and buried photovoltaic (PV) junctions.

In terms of a technical realisation, direct solar-to-chemical energy conversion in PEC cell is considered to be more practical, efficient and less expensive method of H$_2$ production compared to electrolysis of water using PV-generated electricity, because the former integrates light energy collection and water splitting into one device [3][6][7][1]. This goal, however, poses serious material-related challenges: semiconductor photoelectrodes should efficiently harvest solar irradiation and drive water oxidation or reduction reactions in aqueous solutions at a sufficient rate at current densities of (10 - 15) mA.cm$^{-2}$ under 1 Sun illumination without degrading for a sufficiently long period of time, i.e., more than 2000 h according to benchmarks of US Department of Energy [8]. Such a set of requirements simply cannot be met by a single material, therefore formation of various heterostructures [9][10][11][7][12][13][14][15], tandem devices [16][17][18], as well as methods for photocorrosion protection of semiconductors [19][20][21][22][23] have been very intensively explored over the period of recent years in 2010 - 2015, as can be seen from the list of the referenced literature.

1.2. Recent state-of-the-art in solar water splitting

The highest solar-to-hydrogen efficiencies (STH), exceeding 10%, so far have been achieved using very expensive and unstable III-V group semiconductors [24][25]. Therefore the focus of undergoing research is to find economically viable, efficient and stable material compositions for PEC water splitting based on earth-abundant elements. A great deal of attention is being devoted to employment of Si photovoltaics in solar hydrogen production, as this technology is well-developed already and, more importantly, the price of crystalline silicon solar cells has decreased more than 7 times in the past several years [26]. Reece et al. [12] has reported fabrication of solar water-splitting cells, which consist of triple junction amorphous Si photovoltaic cell interfaced to cobalt borate and NiMoZn as oxygen and hydrogen evolution catalysts, respectively. The highest STH efficiency obtained was 4.7% under 1 Sun illumination, however, a stable operation of the device lasted only for 10 hours. Another group [21] has
Figure 1: n-Si/Ni Schottky solar cells connected in series under natural Sun illumination (on 11:20 am, 4 March 2014, Swinburne Uni., Melbourne, Australia). The open circuit voltage, $V_{OC}$, and short circuit current, $I_{sc}$, readings are shown on the multimeter. Single cell area was $\sim 2 \times 2 \text{ cm}^2$. Inset shows schematics of the layers in the n-Si/Ni Schottky diode solar cell. The Ni and Ti were magnetron sputtered films; native SiO$_2$ of $\sim 2 \text{ nm}$ was on the surface of n-type Si.

successfully stabilized silicon photoanode by atomic layer deposition (ALD) of 2 nm thick layer of TiO$_2$ covered with 3 nm thick iridium film for the OER catalysis. Stable operation of the anode was observed for at least 24 hours. Similarly, ALD-grown Al-doped ZnO (20 nm) and TiO$_2$ (20 nm) protective layers modified with Pt nanoparticles have been shown to effectively stabilize Cu$_2$O photocathode for H$_2$ production, which retained 62% of the initial photocurrent value after 10 hour stability test. Recently, a 40-h-long stable operation of tandem-junction GaAs/InGaP photoanode, protected with ALD-formed TiO$_2$ layer, in conjunction with Ni-based HER and OER catalysts, was reported. Kenney et al. demonstrated a record 80 h long direct water oxidation, using n-type Si photoanodes passivated with a 2 nm thick nickel film, which acts also as oxygen evolution catalyst.

Thus, one has to admit that significant progress has been made in recent years in the area of engineering the semiconductor electrodes for efficient solar water splitting, however, the fabrication of complex heterostructures usually involves such sophisticated techniques as ALD, which are totally incompatible with the larger area and mass production of the photoelectrodes, if solar energy is going to be collected on the terawatt scale. Moreover, the longevity of these state-of-the-art photoelectrodes is still far beyond the targeted 2000 hours and the energy conversion efficiency achieves the pursued 10% only when the most expensive III-V semiconductors are used.

In view of the above, the so-called “brute-force” or photovoltaic (PV) plus the electrolysis approach is lately being reconsidered. The main advantage of this approach is that both processes, i.e., the photovoltaic and electrochemical energy conversion can be optimized independently. Moreover, the problems related with photo-corrosion of semiconductors and blocking of the light-sensitive surface with HER or OER catalyst particles are automatically...
avoided. In ref. [31] $\eta_{STH} = 18\%$ was obtained using system integrating highly efficient, yet very expensive, group III-V semiconductor solar cells, optical concentrator and polymer electrolyte membrane electrolyzer. Quite recently [20] STH efficiency exceeding 10\% has been achieved with a crystalline silicon PV module and noble metal-free, low cost HER and OER catalysts. The operation of the coupled system was stable for over a week at current density of $\sim 8 \text{ mA.cm}^{-2}$. For practical applications an expectation of a lifetime for a solar energy converter is dictated by solar cells and has to be 25 years. Thus, it is evident, that in construction of efficient solar water splitting system, a trade-off between efficiency, cost and longevity must be achieved.

Here, we explicitly demonstrate that by separating steps of: (1) solar-to-electrical and (2) electrical-to-hydrogen conversion the highest overall solar-to-hydrogen efficiency $\eta_{STH}$ can be achieved. As tutorial case study, we choose a simple Si/Ni Schottky solar cell for the process (1) and the most efficient Pt and Ti/Ir-Ta oxide electrodes as HER and OER catalysts for the process (2). The mechanism of water splitting reactions based on the principles of thermodynamics are revealed and the reason of absence of water splitting at the thermodynamically predicted 1.23 V potential are given.

2. Samples and methods

To investigate the efficiency of water splitting a simple setup was made using a Schottky solar cell and connecting it to a water splitting cell.

2.1. Fabrication of Schottky solar cells

Solar cell was made on a $2 \times 2 \text{ cm}^2$ n-type Si wafer (0.4 mm thick) by sputtering 15-nm-thick Ni layer for the front (illuminated) side and a 20 nm back side Ti contact (Fig. 1), the photoanode design used for the water oxidation [13]. Metal coatings were sputtered using AXXIS (JKLesker) physical vapor deposition setup. Si (100) wafers were n-type of a 0.3-0.5 $\Omega\cdot\text{cm}$ resistivity (University Wafers). The values of the open-circuit voltage, $V_{oc}$, and short-circuit current, $I_{sc}$, of three cells connected in series and measured with multimeter under natural outdoor illumination conditions were 0.87 V and 10.3 mA, respectively (Fig. 1).

In order to efficiently drive water-splitting reactions, the voltage applied on water electrolysis cell should exceed 1.8 V [16], therefore we used the battery of nine Schottky solar cells in our experiments. A home designed solar simulator was used for experiments of solar-to-hydrogen conversion. A high intensity discharge Xe-lamp with 6000 K spectrum was used to illuminate solar cells using a collimating lens and was calibrated with a silicon diode to have approximately 50 mW.cm$^{-2}$ irradiance (0.5 Sun) at 30 cm from the lamp over the area of $5 \times 5 \text{ cm}^2$.

Current-voltage $I - V$ characteristics of the battery of Schottky solar cells were measured using Keithley 2400 SourceMeter. The $I - V$ response upon illumination was measured using the same illumination device and conditions
as in the electrochemical experiments, namely, the intensity of illumination was 50 mW.cm$^{-2}$ (0.5 Sun).

2.2. Electrochemical measurements

The PV-assisted water electrolysis experiments were performed in glass cell of 30 cm$^3$ volume using Pt cathode ($S_c = 1$ cm$^2$) for HER and dimensionally stable (DSA) titanium anode ($S_a = 1$ cm$^2$) with catalytic layer of mixed iridium and tantalum oxides (Elade Technology Co. Ltd, China) for OER. Electrolyte was aqueous solution of 0.5 M Na$_2$SO$_4$ and 0.1 M KOH. Reagents of analytical grade and deionized water were used to prepare the solution. The operating voltage, $V_{op}$, and the operating current density, $i_{op}$, in the water electrolysis cell between the anode and cathode, connected through 1 Ω resistance, were measured using potentiostat-galvanostat PI-50-1 connected to computer through an analogue-digital converter interface.

Cyclic voltammetry was used to test the individual performance of the above described anode and cathode in the same electrolyte solution. The experiments were performed using potentiostat/galvanostat AUTOLAB 302 and three-electrode electrochemical cell. Pt plate served as counter electrode (CE) and reversible hydrogen electrode in working solution (RHE) was used as the reference. Potential values in the text refer to the RHE scale, unless noted otherwise. The conversion between RHE and standard hydrogen electrode (SHE) scales can be done according to equation: $E_{\text{vs.SHE}} = E_{\text{vs.RHE}} - 0.059\text{pH}$. All experiments were performed at room conditions.

3. Results: water splitting

Efficiency analysis of the two intermediate steps in solar-to-hydrogen conversion: (1) solar-to-electrical and (2) electrical-to-hydrogen are tested using simple solar cell and water splitting cell.

3.1. I-V characteristics of Schottky solar cells

Figure 2(a) shows the photo of battery of n-Si/Ni Schottky solar cells connected in series and mounted on a slice glass, which was used in water-splitting experiments. Figure 2(b) shows the current-voltage, I-V, characteristics of this battery in dark and under artificial 0.5 Sun illumination with a typical voltammetric response of a Schottky photodiode. Figure 2(c) illustrates the determination of the fill factor for the battery of 9 cells, $FF = P_{\text{max}}/(V_{oc} \times I_{sc})$, where $V_{oc}$ is the open-circuit voltage, $I_{sc}$ is short-circuit current, and $P_{\text{max}}$ is the maximum power, measured under 0.5 Sun artificial illumination. The $FF$ value was further used for the estimation of the light-to-electric (photovoltaic) energy conversion efficiency, $\eta_{PV}$, which is defined as the ratio between useful power output $P_{\text{out}}$, and total light power input $P_{\text{in}} = S \times I$ factored over the solar harvesting area $S$:

$$\eta_{PV} = \frac{P_{\text{max}}}{P_{\text{in}}} = \frac{I_{sc}V_{oc} \times FF}{S \times I}, \quad (1)$$
Figure 2: (a) Solar cell battery assembled from cells shown in Fig. 1 used in experiments of water splitting; (b) I-V plot for nine cells connected in series in dark and under artificial 0.5 Sun illumination. (c) Determination of the fill factor, FF, of the battery of nine cells under an artificial 0.5 Sun illumination: \( V_{OC} = 2.95 \text{ V} \), \( I_{sc} = 11.2 \text{ mA} \), \( P_{max} = 12.1 \text{ mW} \) yielding FF = 0.37. The \( \otimes \) marker shows the working point voltage in the case of solar water splitting using solar cell battery coupled with water electrolysis cell.

where light intensity was \( I_l = 50 \text{ mW/cm}^2 \) or 0.5 Sun used in experiments and as harvested over \( S = 9 \times (2 \times 2) = 36 \text{ cm}^2 \) area.

Rather small values of FF = 0.37 and \( \eta_{PV} \approx 0.68 \% \) were obtained. As one can see from Fig. 2(c), the current at maximum power point is \( \sim 7 \text{ mA} \). Having in mind large area of illuminated surface as well as low value of fill factor, one has to admit that n-Si/Ni Schottky solar cell is not an optimal choice, however, its operation in air atmosphere is stable; as a photoanode in direct water splitting the same Schottky barrier has lifetime < 100 h \[13\]. This simple solar cell is used here to reveal factors defining the efficiencies of an overall solar-to-hydrogen conversion and to show pathway to the highest values. From the slope of I-V curve in dark (Fig. 2(b)) the resistance of the battery of 9-cells in series was evaluated as \( \approx 130 \Omega \) or \( R_{1 cell} = 15 \Omega \) due to a native oxide layer.

3.2 Water splitting: choice of electrodes

Pt cathode was chosen for the hydrogen evolution reaction. Though Pt is expensive material, it is the best and stable HER catalyst in both acidic and alkaline solutions \[32\]. Commercially available dimensionally stable titanium-supported iridium/tantalum oxide-based anode was tested for oxygen evolution reaction. To evaluate the overpotentials of hydrogen and oxygen evolution reactions, cyclic voltammograms of the chosen electrodes were recorded in the solution of 0.5 M Na\(_2\)SO\(_4\) and 0.1 M KOH and are shown in Fig. 3. The areas negative and positive to vertical lines at \( E = 0 \text{ V} \) and \( E = 1.23 \text{ V} \), correspond to overpotentials of HER and OER, respectively. It should be noted, however, that ohmic potential drop due to resistance of the electrolyte is not taken into consideration in Fig. 3 however it has a minor effect.
3.3. Water splitting powered by Schottky solar cell

We coupled photovoltaic and electrochemical systems in the most simple way, i.e., by wiring the positive and negative terminals of solar cell battery (Fig. 2(a)) to anode and cathode of the water electrolysis cell, respectively. Evolution of gases on both electrodes was recognized almost instantaneously by formation of micro-bubbles (see, the supplement movie) after switching the light illumination (Fig. 4(a)).

Initially, upon switching on the light, the operating current density, $i_{op}$, in the water electrolysis cell jumped to $\sim 8 \, mA.cm^{-2}$. Then a stationary value of $\sim 3 \, mA.cm^{-2}$ was attained within half an hour (Fig. 4(b)). Chopping of illumination resulted in reproducible current density transients. The variation of the operating voltage $V_{op}$ of the cell during electrolysis under constant and chopped illumination is shown in Fig. 4(c). The stationary value was $V_{op} = 2.37 \, V$. Given such operating voltage, the water splitting reactions, in accordance with Fig. 3, could be driven at the rate of $\sim 7 \, mA.cm^{-2}$, however, the actual values are dictated by the I-V characteristic (low $FF$) of the PV power source (see the working point of coupled system indicated in Fig. 2(c)) and the resistance of the whole circuit.

The overall or solar-to-fuel efficiency of the system can be calculated according to the following equation:

$$\eta_{STH} \equiv \eta_{PV} \times \eta_{ec} \times \eta_{co},$$  \hspace{1cm} (2)

where $\eta_{PV}$ is the efficiency of light-to-electric energy conversion, $\eta_{ec}$ is the efficiency of electric-to-chemical energy conversion and $\eta_{co}$ is the efficiency of coupling of the two systems [33]. The efficiency of the electrochemical water splitting is:

$$\eta_{ec} = [1.23 \, V \times I_{op}] / [I_{op}V_{op}] \simeq 0.52 \quad (or \ 52\%),$$  \hspace{1cm} (3)

where 1.23 V corresponds to the thermodynamic potential of water splitting reaction, $I_{op} = 3 \, mA$ is the operating current through the water electrolysis cell at $V_{op} = 2.37 \, V$. The coupling efficiency can be evaluated on the basis of the following reasoning. The photovoltaic efficiency of the solar cell battery at the operating point is $\eta_{op} = I_{op}V_{op} / [S \times I_1] \simeq 0.4\%$, while the maximum $\eta_{PV}$ is 0.68\% (see Eqn. 1). Consequently, the coupling efficiency can be calculated according to: $\eta_{co} = \eta_{op} / \eta_{PV} \simeq 0.59 \, (59\%)$. Hence, the overall cumulative efficiency of solar-to-hydrogen conversion is $\eta_{STH} \simeq 0.68 \times 10^{-2} \times 0.59 \times 0.52 = 0.21\%$.

In order to achieve higher values of energy conversion efficiency, more efficient photovoltaics should be used. Efficiency of the electrolysis is not a limiting factor in this case. The coupling efficiency of 59\% in this case study is due to an electrical impedance mismatching and could be further improved. Despite low value of $\eta_{STH}$, such method of solar hydrogen production by separating (1) solar-to-electrical and (2) electrical-to-hydrogen steps could be competitive considering its long term stability.
Figure 3: Cyclic voltammograms of Pt cathode and Ti/(Ir-Ta) anode in HER and OER regions, respectively, solution 0.5 M Na$_2$SO$_4$ + 0.1 M KOH, potential scan rate 10 mV.s$^{-1}$. The arrow at $E^0 = 1.77$ V marks the standard potential of H$_2$O$_2$ formation which is suggested to be the threshold potential in oxygen evolution reaction (see, Eqns. 4, 5). Electrode anode and cathode area in experiments of water splitting was $S_{a,c} \sim 1$ cm$^2$.

4. Discussion

The presented tutorial demonstration of solar hydrogen production with $\eta_{SHT} \approx 0.21\%$ efficiency using a low efficiency $\eta_{PV} \approx 0.68\%$ solar cell is analysed next for more practical implementation and analysis of fundamental limitations.

4.1. Some mechanistic aspects of water splitting reactions

From the thermodynamic point of view, the voltage of only 1.23 V should be sufficient to electrolytically split water into O$_2$ and H$_2$, since $E^0_{O_2/H_2O} = 1.23$ V and $E^0_{H^+/H_2} = 0$ V under standard conditions. However, as it can be explicitly seen in Fig. 3 at $\Delta E = 1.23$ V the current density $i \approx 0$. It is well known that modern alkaline electrolyzers operate at voltages exceeding 1.8 V [16, 1] and appreciable rate of HER and OER is achieved at 2.0 - 2.5 V. It is also well-known that HER can be catalyzed at the overpotentials much lower than those of OER [33, 32]. The mechanism of hydrogen evolution reaction (HER) on Pt electrode mediated by molecular hydrogen ion has been described earlier [34, 35, 36]. The mechanism of oxygen evolution reaction (OER), taking place on the oxidized metal electrode surface, should involve formation of hydrogen peroxide as intermediate, followed by its oxidation to O$_2$ according to equations as follows:

$$2H_2O - 2e^- \leftrightarrow H_2O_2 + 2H^+, \quad E^0 = 1.77 \ \text{V}, \quad (4)$$

$$H_2O_2 - 2e^- \leftrightarrow O_2 + 2H^+, \quad E^0 = 0.68 \ \text{V}. \quad (5)$$

Such layout of the $E^0$ values of reactions 4 and 5 means that, once formed, hydrogen peroxide is spontaneously oxidized to O$_2$. Sum of these two reactions divided by 2 gives the formal equation of the OER:

$$H_2O - 2e^- \leftrightarrow 1/2O_2 + 2H^+, \quad E^0 = 1.23 \ \text{V}, \quad (6)$$
while the process, actually, does not follow this path (see OER region in Fig. 3). Therefore, reaction (4) with $E^0 = 1.77$ V should be considered to be the main energetic barrier in H$_2$O splitting process. Since thermodynamically oxidation of water is allowed at 1.23 V, it can be depolarized in the range between 1.23 V and 1.77 V with a help of suitable electrocatalysts. The mechanism of electrocatalytic OER taking place in the case of Ru and Ni electrodes and involving the formation of metal surface peroxo species has been proposed [37, 38].

In the case of photolytic water splitting on the semiconductor surface, the photon with an energy of 1.23 eV ($\lambda \approx 1 \mu$m) is able to break one O-H bond in H$_2$O molecule. So, to break both bonds, two such photons are needed, i.e., thermodynamic work equivalent to $\sim 2.46$ eV should be performed. The same amount of energy is gained when one mole of H$_2$ gas is burned in O$_2$ atmosphere. The same work would be performed by two photons with the energies of $\geq 1.77$ eV $+ 0.68$ eV, or one photon with the energy of $\geq 2.46$ eV. Thus, in terms of energy, the expenses in both cases, i.e. electrolytic and photolytic water splitting, are the same.

4.2. Approaching theoretical limits

An understanding of fundamental mechanisms of solar-to-electrical energy conversion has recently resulted in fast progress towards theoretical Shockely-Queisser 33.5% limit of solar energy harvesting. It has been demonstrated [39], that solar-to-electrical conversion up to 28.8% can be achieved using direct bandgap GaAs material with inherently large luminescence yield of 99.7%, due
to augmented $V_{OC} = 1.12$ V. This corresponded to a 2.4% increase made in one year from the previous record in GaAs; a 30% efficiency seems is in reach in the near future. The record high efficiency will be achieved in few micrometers thin solar cell. In the solar-to-hydrogen conversion, the most efficient method is to separate solar-to-electrical and electrical-to-chemical (via electrolysis) parts as shown in this study. Understanding of HER and OER mechanisms at molecular level is essential in search for the most efficient water splitting catalysts. Storing of solar energy in the form of chemical bonds (hydrogen) is providing a method to solve inherent inefficiencies in the day-night and summer-winter solar energy cycling.

The current household PV panels are working at $\eta_{PV} \simeq 18\%$ and the water electrolysis efficiencies of $\eta_{ec} \simeq 60\%$ are typical [40]. For the current state-of-the-art, the overall efficiency of solar hydrogen production and ideal $\eta_{co} = 100\%$ (achievable via micro-invertor control) is expected to approach (Eqn. 2): $\eta_{STH} = 0.18 \times 0.6 \simeq 0.11 \ (11\%)$. This estimate shows that separation of solar-to-electric and electric-to-chemical processes and increasing their efficiencies $\eta_{PV}$ and $\eta_{ec}$ is an unrivaled approach for future solar hydrogen technology. The efficiencies achievable today are more that one order of magnitude larger as compared with direct light-to-hydrogen conversion efficiencies. Moreover, those direct water splitting solutions have not reached required long term stabilities of the process (years of operation are required).

For practical use of solar hydrogen in future, sea water has to be used. This would further complicate electrode stability for the direct light-to-hydrogen conversion schemes which are even not currently researched. Desalination of water is an expensive process as it uses large amounts of energy, therefore new anode materials should be designed, that would preferentially evolve oxygen instead of chlorine from seawater [3]. Manganese-tungsten oxides deposited on iridium-oxide coated titanium have been shown to suppress chlorine evolution and enhance the OER in seawater electrolysis [41]. Ti-supported catalytic layer of mixed Ru and Ni oxides has been suggested as the electrode material suitable for obtaining pure oxygen from sea water alkalized to $\text{pH} \geq 14$ [37].

5. Conclusions

Critical analysis for available literature on solar hydrogen generation is presented with a case study analysis using a simple solar cell and performing water splitting in an electrolysis cell.

It is demonstrated that a very simple battery of n-Si/Ni Schottky type solar cells can be used for the solar hydrogen generation with $\sim 0.2\%$ efficiency, when the processes of solar energy harvesting and electrolysis are separated. Low efficiency of light-to-electric energy conversion, $\eta_{PV} = 0.68\%$, is shown to be a limiting factor in the overall process of light-to-chemical energy conversion in this analysed case.

It is suggested that oxidation of water to hydrogen peroxide with $E^{0}_{H_{2}O_{2}/2H_{2}O} = 1.77 \text{ V}$ should be considered as the main energetic barrier in oxygen evolution reaction. Even with such low efficiency $\eta_{STH} = 0.2 \%$, the described way of solar...
hydrogen production could be competitive considering the long term stability of operation of the coupled systems. Directions for efficient and practical solutions in solar hydrogen production based on mechanism and considering current and future PV technology are presented.

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