# Case study: Technical assessment of the efficiency optimization in direct connected PV-Electrolysis system at Taleghan-Iran

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**Abstract:** The use of PV array energy in supplying the electrolyzer systems is very suitable. During the daylight hours, the sunlight converts by PV array into electrical energy which will be used for electrolyzing process. Then hydrogen produced by the electrolyzer is compressed and stored in hydrogen vessel. This provides energy for the fuel cell to meet the load when the solar energy is insufficient. Solar hydrogen technology is relatively simple and the only raw material for the production of solar hydrogen is water. In this study technical results obtained from direct connection of 10 kW PV array with 5 kW electrolyzer systems for hydrogen production and storage at Taleghan site. Variations of the solar radiation intensity, hydrogen production rate, solar hydrogen efficiency and overall efficiency of solar hydrogen energy were considered as base of analyses. It is found that the minimum and maximum overall energy efficiency values of the system are 0.93 % and 5.01 %, respectively. The result shows a great potential in direct solar radiation for absorbing and converting it to other types of energy in Iran. Using solar energy required high initial investment, so converting solar energy to other types of energy with high efficiency systems is vital.

***Keywords:*** *Photovoltaic, Water Electrolysis, Hydrogen Production, System Efficiency, Taleghan*

## Nomenclature

| | | |
|---|---|---|
| $E$ | *calorific value of hydrogen* | $J.ml^{-1}$ |
| $Q$ | *hydrogen production rate* | $ml.sec^{-1}$ |
| $S$ | *solar radiation intensity* | $W.m^{-2}$ |
| $A$ | *PV array surface* | $m^2$ |
| $I_e$ | *current* | $A$ |
| $T_c$ | *the PV cell temperature* | $^oC$ |
| $T_r$ | *PV cell reference temperature* | $^oC$ |
| $v$ | *hydrogen production* | $m^3.hr^{-1}$ |
| $\beta$ | *Temperature coefficient of a solar cell in STC* | $°C^{-1}$ |

## 1. Introduction

As conventional fossil fuel energy sources diminish and the world's environmental concern about acid deposition and global warming increasing, renewable energy (RE) resources are attracting more attention as alternative energy sources [1]. The use of RE resources, which do not endanger the environmental balance, is a way to solve many of the environmental problems caused principally by the excessive use of fossil fuels. RE resources are free of pollution during their development and operation for power generation [2]. RE systems based on intermittent sources exhibit strong short term and seasonal variations in their energy outputs. Therefore, the need for storage of energy arises; storing the energy produced in periods of low demand to utilize it when the demand is high, ensuring full utilization of intermittent sources available [3]. Solar photovoltaic energy has been widely utilized in small size application and is the most promising candidate for research and development for large-scale use, as the fabrication of less costly photovoltaic devices becomes reality [1]. Hydrogen holds a preeminent position among the solar fuel candidates because of its high energy content, low environmental effect, storage compatibility and distribution [4-6]. Solar hydrogen is described as a potential energy storage medium to offset the variability of solar energy [7]. The seasonal storage of solar energy in the form of hydrogen can provide the basis for a completely renewable energy system [8]. Hydrogen can be generated by using different technologies, but only some of them are environmentally friendly. It is argued that hydrogen generated from electrolyzing water is a leading candidate for a r enewable and environmentally safe energy carrier due to the following reasons [9]:

- Solar hydrogen technology is relatively simple and, therefore, the cost of such a fuel is expected to be substantially less than the present price of gasoline.
- The only raw material for production of hydrogen is water, which is a renewable resource.
- Large areas of the globe have access to solar energy which is the only required energy source for solar hydrogen generation.

Country of Iran with more than 4.5 kWh/m$^2$.day radiations has a great potential for converting solar radiation to electricity. One of the efforts done in the field of constructing and utilization solar hydrogen plant is constructing stand-alone energy system PV-electrolyzer-fuel cell in Taleghan-Iran. The purpose is to demonstrate the technical feasibility of using hydrogen as solar energy storage medium. This small scale demonstrative energy system uses PV as the primary energy conversion technology, hydrogen as the storage medium and a fuel cell as the regenerative technology [10].

## 2. Methodology

In this study, we will evaluate overall efficiency from connection of 10 kW PV array with 5 kW alkaline electrolyzer systems for hydrogen production and storage at Taleghan renewable energies site. We assumed that water electrolysis operated during a sample day in summer season during 150 minutes (10:30 until 12:50). Variations of the solar radiation intensity, hydrogen production rate, solar hydrogen efficiency and overall efficiency of solar hydrogen energy in operating conditions were gathered and considered as base of analyses.

## 3. Results

### *3.1. Description of the solar hydrogen energy system*

This energy system is located in a mountainous area with latitude N 36$^o$, 8', longitude E 50$^o$, 34' and altitude 1700 m. The system consists of a 10 kW photovoltaic (PV) array coupled to a 5 kW bipolar, alkaline electrolyzer, and a gas hydrogen storage tank. When the sun shines, PV power is available and directly supply the load. By this power electrolyzer produces hydrogen, which is delivered to the hydrogen storage tanks. When PV array cannot provide electricity, the 1.2 kW PEM fuel cell will begin to produce electricity. Hydrogen in storage tank prepares the feed of fuel cell for production of needed electricity [11].

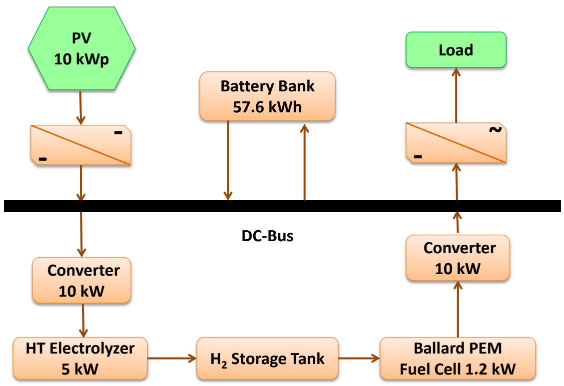


*Fig. 1. Schematic of solar hydrogen energy system at the Taleghan site*

Experimental results for the operation of directly coupled PV-electrolyzer in operating regime of electrolyzer for a sample day in summer are presented. The schematic of this energy system is given in Fig. 1.

### *3.2. Photovoltaic array*

Solar energy is one type of the RE resources, which can be converted easily and directly to the electrical energy by PV converters. The PV module is a polycrystalline silicon type with maximum output of 45 W, an open circuit voltage of 20.5 V and 10 kW PV array consists of 224 solar panels MA36/45 modules installed at the Taleghan site. The PV array has a fixed inclination of 45 degree with horizontal and it is mounted such that the module is facing south direction [12]. Each module is 462 mm wide and 977 mm long for an area of 0.45 $m^2$ per module and total surface of 101.1 $m^2$ ($2\times7\times16\times0.45 \approx 101.1$ $m^2$). This angle corresponds to the optimum tilting in spring for the installed PV and is the latitude of Taleghan area. The power also depends on temperature, wind speed, and age of cells. The efficiency ($\eta_e$) of a solar cell is a function of the cell temperature ($T_c$) and it is defined as:

$$\eta_e = \eta_r\left[1-\beta\left(T_C - T_r\right)\right] \qquad (1)$$

Where $\eta_r$ is the efficiency of a solar cell at standard conditions, $T_c$ the temperature of PV cell (°C), $T_r$ the PV cell reference temperature, and $\beta$ is the temperature coefficient of a solar cell in STC (that for PV module is a polycrystalline silicon is 0.0004 $°C^{-1}$) [13-14].

*Table 1.Parameters related to solar radiation, ambient temperature and power system vs. time*

| Time | Insolation ($W/m^2$) | Ambient temp. (°C) | Module temp. (°C) | Power system (kW) | Efficiency system (%) |
|---|---|---|---|---|---|
| 6 a.m. | 26 | 19 | 20 | 0.2989 | 11.45 |
| 7 a.m. | 79 | 20 | 22 | 0.9045 | 11.41 |
| 8 a.m. | 176 | 20 | 24 | 1.9988 | 11.32 |
| 9 a.m. | 387 | 21 | 29 | 4.3236 | 11.13 |
| 10 a.m. | 553 | 22 | 33 | 6.1016 | 10.99 |
| 11 a.m. | 677 | 24 | 38 | 7.3760 | 10.86 |
| 12 a.m. | 738 | 25 | 40 | 8.0086 | 10.81 |
| 13 p.m. | 731 | 26 | 41 | 7.9306 | 10.81 |
| 14 p.m. | 680 | 27 | 41 | 7.4087 | 10.86 |
| 15 p.m. | 585 | 25 | 37 | 6.4277 | 10.95 |
| 16 p.m. | 402 | 23 | 31 | 4.4912 | 11.13 |
| 17 p.m. | 201 | 20 | 26 | 2.2642 | 11.22 |
| 18 p.m. | 96 | 17 | 21 | 1.0770 | 11.32 |
| 19 p.m. | 36 | 16 | 17 | 0.4138 | 11.45 |
| 20 p.m. | 6 | 15 | 15 | 0.0692 | 11.50 |

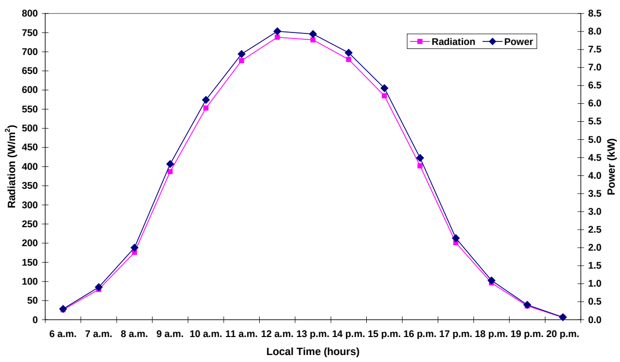


*Fig. 2. Variations of the solar radiation intensity and power of 10 kW PV vs. time for a sample day*

According to data received such as solar radiation intensity, ambient temperature, modules temperature, can be produced solar modules and system efficiency in the period 6 a.m. till

8 p.m. in sample day at Taleghan site was calculated. Parameters related to solar radiation intensity, ambient temperature, modules temperature, power system and solar cell efficiency versus time for sample day are given in Table 1. Variations of the solar radiation intensity, producing power system, efficiency and cell temperature of PV array against to time for a sample day are given Figs. 2 and 3.

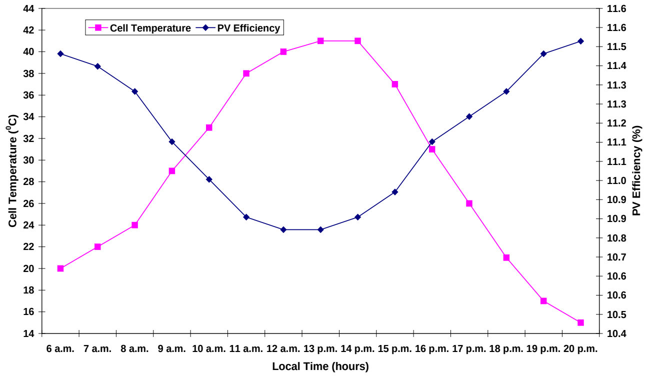


*Fig. 3. Variations of efficiency of PV arrays and cell temperature vs. time for a sample day*

### *3.3. Battery bank*

It is known that a solar hydrogen system needs a storage system to provide energy for the cases of inappropriate weather conditions, instantaneous overload conditions, or demand for energy after sunset [15-16]. Sun irradiance is stochastic variables by nature. Energy storage such as in a battery is required for storing energy from PV array for the back up and stand by power source. The battery type is lead-acid because of the low cost and good electrical performance under various conditions [17-18]. The selection of a proper size of the battery bank for these types of applications requires a complete analysis of the battery's charge and discharge requirements [19-20]. The lead-acid batteries have the longest life and the least cost per amp-hour of any of the choices [21].The battery system is made up of forty-eight deep discharge lead-acid batteries which are installed at the capacity of 57.6 kWh (12V×100 Ah × 48 cell). Each battery has an average lifetime of five years. When the electrolyzer is turn off, the excess energy generated from PV array is used to charge the batteries. If electrolyzer needs more power, the rest of power for operation is supplied by the batteries.

### *3.4. Inverter*

A 10 kW Sunny Boy 2500U model inverter is a single-phase AC power source that is connected between the battery bank and utility grid at 195-251 $V_{AC}$. The battery voltage decrease when the AC loads increase. The inverter is based on a power unit that operates with a very high efficiency and optimal reliability. For more specifications, see Table 2 [22].

*Table 2. Inverter technical characteristics (Sunny Boy model 2500)*

| | | | |
|---|---|---|---|
| $P_{nominal}$ | *2200 $W_p$* | Max. AC-power | *2500 W* |
| Max input voltage | *600 V* | Peak inverter efficiency ($\eta_{max}$) | *93-94.4%* |
| Max input current | *11.2 A* | AC input frequency | *49.8-50.2 Hz* |
| PV-voltage range MPPT | *250-600 V* | $V_{AC}$ | *198-251 V* |

### *3.5. Hydrogen unit*

Water electrolysis technology has the highest energy efficiency in non-fossil fuel based hydrogen production and is ideally suited for coupling with intermittent renewable energy resources [19]. In general, there is a good match between the polarization curves of PV cells and water electrolysis. However electricity from PV is expensive and hydrogen produced from such electricity is even more expensive, but this technology is well developed and matured for a large scale electricity and hydrogen generation [23]. The decomposition of water into hydrogen and oxygen can be achieved by passing an electric current between two electrodes separated by an aqueous electrolyte. The total reaction for splitting water is [24]:

$$H_2O(l) + \text{Electrical Energy} \rightarrow \mathrm{H_2(g)} + \frac{1}{2}O_2(g)$$

In this pilot, the electrolyzer is a bipolar and alkaline type manufactured by the Hydrotechnik (Germany). The electrolyzer module consists of 10 c ells in series. The nominal operating point is rated load, 250 amperes and rated voltage, 25 $V_{max}$. The electrolyte (KOH) concentration inside the cells is about 28 wt. %.; the amount of hydrogen produced in one hour by the electrolyzer is found by the formula:

$$v = 0.000419 \times I_e \times A \times n = 4.12 \times 10^{-3}.I_e \quad (\mathrm{m^3/hr}) \tag{2}$$

where $I_e$ is the current (in Ampere), $A$ is a coefficient, $n$ is number of electrolytic cells, and ν is the hydrogen production in $m^3$/hr. Hydrogen is stored at 10 bars in a tank to feed the fuel cell at low solar radiation levels and hence supply the required load power [25]. The maximum stable rate of hydrogen production was about 1 $Nm^3$/hr. The electrolysis efficiency is about 70 %, based on the HHV (Higher heat Value) [26].

$$P_{out} = 1\left(\frac{m^3}{hr}\right) \times \frac{1(\mathrm{mol\,H_2})}{22.4(lit)} \times \frac{285830(J)}{1(\mathrm{mol\,H_2})} \times \frac{1(hr)}{3600(\sec)} \times \frac{1000(lit)}{1(m^3)} = \frac{285830000}{80640} = 3544\mathrm{W}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{3544(W)}{5000(W)} = 0.7089 \tag{3}$$

The oxygen output still contains small amounts of hydrogen gas and vast amounts of water vapor. It was not used in this system and was released into the atmosphere [27]. The hydrogen from the electrolyzer is sent into a low pressure tank (buffer tank) that is kept at a pressure lower than the hydrogen output pressure of the high pressure tank as shown in Fig. 4.

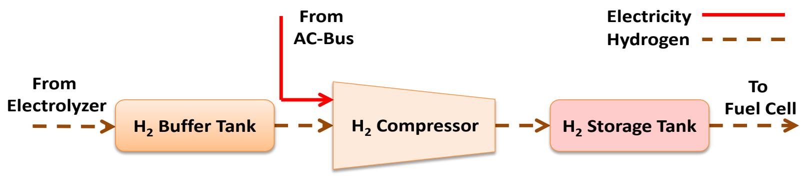


*Fig. 4. Schematic of hydrogen storage system*

Compression occurs during compressor cycles in which the hydrogen is continuously removed from the low-pressure tanks beginning at the current pressure of the low-pressure tank and ending when the pressure drops to a specified minimum supply pressure. The volume of hydrogen vessel is 1 $m^3$ and maximum pressure is 10 bars. It is known that a stand-alone photovoltaic system needs a storage system to provide energy for the cases of inappropriate weather conditions, instantaneous overload conditions, or demand for energy after sunset [28]. Due to simple operation, high efficiency and ability to provide power quickly from a standby configuration, a PEM fuel cell was chosen for this project. This system manufactured by Ballard power system Inc.(Canada) that has 30 cells and provides up to 1.2 kW of unregulated DC power at a nominal output voltage. The output voltage varies with power, ranging from about 43 V at system idle to about 26 $V_{DC}$ at full load. It has the capability to operate at low temperature and has short start-up period [29] .Overall system efficiency for the direct coupling system calculated according to the following equation:

$$\eta_{overall} = \frac{Q \cdot E}{S \cdot A} \tag{4}$$

where $A$ is the PV array total surface (m$^2$), $Q$ is hydrogen production rate (ml/sec), $E$ is the calorific value of hydrogen (J/ml), and $S$ is solar radiation (W/m$^2$) [30].

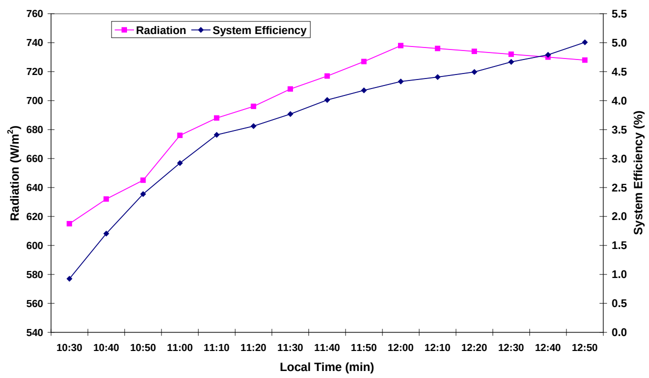


*Fig.5. Variations of solar radiation intensity and solar hydrogen efficiency for a sample day*

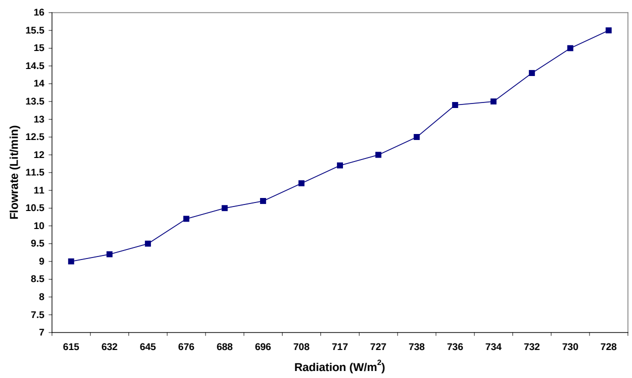


*Fig.6. Variations of HPR vs. solar radiation*

Hydrogen gas has the highest calorific value. When one gram of hydrogen is burnt completely, it produces 150 kJ. Thus the calorific value of hydrogen is 150 kJ/g (≈12.6 J/mol) [31]. We assumed that water electrolysis operated during a sample day in summer season during 150 minutes (10:30 a.m. until 12:50 a.m.).

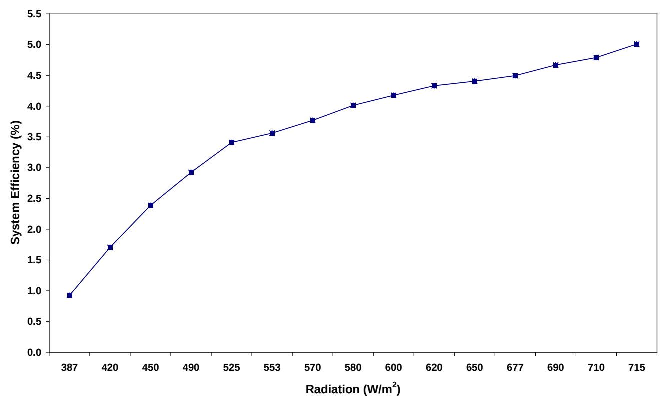


*Fig.7. Variations of solar hydrogen system efficiency vs. solar radiation*

Overall efficiency of solar hydrogen system in this time is shown that in Table 3; also variations of the solar radiation intensity and solar hydrogen efficiency versus time are shown in Fig. 5 and variations of hydrogen production rate and solar hydrogen energy system efficiency versus solar radiation intensity are shown in Figs.6 and 7. The effects of hydrogen production rate and solar radiation on the overall efficiency system are also given in Table 3 and are plotted in Fig. 7. The increase in overall efficiency was from 0.93 to 5.01 % with the increase in current from 25 to 250 amperes, module temperature from 34 to 41$^{o}$C and hydrogen production rate from 9 to 15.5 lit/min.

*Table 3. Parameters related to solar radiation, ambient temperature and power system vs. time*

| Time | Voltage (V) | Current (A) | Hydrogen Production rate (lit/min) | Insolation (W/m$^2$) | Ambient Temp. ($^{o}$C) | Module Temp. ($^{o}$C) | Overall Efficiency System (%) |
|---|---|---|---|---|---|---|---|
| 6 a.m. | 20.2 | 25 | 9.0 | 615 | 23 | 34 | 0.93 |
| 7 a.m. | 21.4 | 50 | 9.2 | 632 | 23 | 35 | 1.70 |
| 8 a.m. | 21.8 | 75 | 9.5 | 645 | 23.5 | 36 | 2.39 |
| 9 a.m. | 22.3 | 100 | 10.2 | 676 | 24 | 38 | 2.92 |
| 10 a.m. | 22.6 | 125 | 10.5 | 688 | 24 | 38.5 | 3.41 |
| 11 a.m. | 22.7 | 137.5 | 10.7 | 696 | 24.5 | 39 | 3.56 |
| 12 a.m. | 22.8 | 150 | 11 | 708 | 24.5 | 39 | 3.77 |
| 1 p.m. | 22.9 | 162.5 | 11.5 | 717 | 24.5 | 39.5 | 4.01 |
| 2 p.m. | 23 | 175 | 12 | 727 | 25 | 40 | 4.18 |
| 3 p.m. | 23.1 | 187.5 | 12.5 | 738 | 25 | 40 | 4.33 |
| 4 p.m. | 23 | 200 | 13 | 736 | 26 | 40 | 4.41 |
| 5 p.m. | 22.8 | 212.5 | 13.5 | 734 | 26.5 | 40 | 4.49 |
| 6 p.m. | 22.7 | 225 | 14 | 732 | 26.5 | 40 | 4.67 |
| 7 p.m. | 22.4 | 237.5 | 15 | 730 | 27 | 40.5 | 4.79 |
| 8 p.m. | 21.7 | 250 | 15.5 | 728 | 27 | 41 | 5.01 |

## 4. Conclusions

- The coupling of PV filed and an electrolyzer allows converting renewable electricity into time-stable storage. The time of storage can be unlimited and there is no loss of energy in stored energy. Using a fuel cell provide a silent electricity generator which has no environmental impact.
- The replacement of conventional technologies like batteries by new hydrogen technologies including using fuel cells in RE based stand-alone power systems is technologically feasible. It reduces emissions, noise and fossil fuel dependence and increases renewable energy penetration.
- New energy generators for stand-alone applications are expected to increase the comfort of people. The actual solutions are either limited by a low autonomy inducing reduction of the electricity consumption during worst seasons or noisy and using fossil energy.
- Iran country located on solar belt and has a great potential in direct natural solar radiation. Solar energy required high initial investment, so converting solar energy to other types of energy with high efficiency systems is vital.

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