POTENCY OF SOLAR HYDROGEN GENERATION SYSTEM IN URBAN AREA: CASE STUDY OF BANDUNG CITY

POTENSI SISTEM PRODUKSI HIDROGEN MENGGUNAKAN PANEL SURYA DI AREA PERKOTAAN: STUDI KASUS DI KOTA BANDUNG

Pramujo Widiatmoko, Hary Devianto, Isdiriayani Nurdin, Saumi Febrianti Khairunnisa, and Muhammad Irfan Rafi

Program Studi Teknik Kimia - Institut Teknologi Bandung
Jl. Ganesha No. 10, Bandung, Telp. & Fax (022) 250 0935
Email: pramujo@che.itb.ac.id

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ABSTRAK

Pengembangan sistem produksi hidrogen sangat penting untuk mendukung pengoperasian kendaraan listrik di masa depan. Penelitian ini mempelajari potensi dari pemasangan sistem *PV-PEM electrolyser* yang terhubung dengan stasiun pengisian bahan bakar di area Kota Bandung. Kemiringan atap dan orientasi panel surya mempengaruhi jumlah energi listrik sebesar 0,8 – 4,2% dari panel surya yang dipasang secara horizontal. Dengan efisiensi *solar-to-hydrogen* sebesar 8,5%, atap perumahan yang terpasang sistem *PV-PEM electrolyser* di Kota Bandung dalam radius 500 m dapat menyediakan bahan bakar hingga seratus mobil listrik per hari. Penelitian ini mencakup pula pemetaan potensi produksi *solar hydrogen* di atap perumahan.

Kata kunci: *Solar hydrogen*, atap perumahan perkotaan, prospek aplikasi, PV-PEM

ABSTRACT

Development of hydrogen production system is important in the future to support electric vehicles operation. This paper studies potency of rooftop PV-PEM electrolyser system connected to fuel station in urban area of Bandung City. Rooftop inclination and orientation of the PV influences the generated electricity by 0.8 – 4.2% compared with horizontal installed-PV. With the solar to hydrogen efficiency of 8.5%, we found that the rooftop installed PV-electrolyser system in Bandung City with supporting area with a radius of 500 m is potentially able to provide fuel for up to a hundred vehicles daily. Further, the potency of rooftop solar hydrogen generation was mapped.

Keywords: *Solar hydrogen, urban rooftop, application prospect, PV-PEM*

INTRODUCTION

Development of hydrogen production is the key component in the next era of fuel-cell (FC) electric vehicles [1]. As a tropical region, Indonesia being exposed by a high intensity of solar irradiation (around 4 $kWh.m^{-2}$ daily), which is potential to fulfill the hydrogen demand. Electrolysis of water at low temperature using solar electricity is the most popular methods to produce hydrogen, known as solar hydrogen [2,3]. Solar radiation energy is first converted into electricity by photovoltaic cells (PV), and consecutively used in an electrolyser to generate the hydrogen. The process can be performed in a single process using a photo-chemical electrolysis system [4]. Beside those water electrolysis processes, the solar hydrogen can also be generated using thermolysis and thermochemical cycle methods [5,6]. The solar hydrogen provides advantages on renewable water as energy carrier, abundant amount of sun light, and absence of carbon dioxide emission.

The awareness on solar hydrogen production is growing. Yilanci et al. reported an assessment on photovoltaic-hydrogen/fuel cell hybrid system for stationery application in Denizli, Turkey [3]. Overall energy efficiency of the system varies up to 9.7%, while overall exergy up to 9.3%. Vidueira et al. examined PV system to produce hydrogen and its uses in fuel cell bus for Madrid Municipality [7]. The system is within the Clean Urban Transport for Europe (CUTE) program which is developed around the middle of 2003. Nowotny et al. also reported development of solar hydrogen system and materials under Australia-Japan-Korea Network [8]. One of the aims of the project is to develop solar hydrogen household unit for powering cars, heating, and producing electricity using fuel cell.

In transportation case, it is expected that distribution of fuel-cell vehicles will concentrates in urban areas rather than rural ones, increases demand on solar hydrogen and its support system. Installation of the solar hydrogen system in the urban areas will reduce transportation cost and storage problems. However, there is limitation on availability of installation area.

Rooftop-installed solar panel is a solution for the area limitation in the urban. Izquierdo, *et al.* developed a method to estimate potential of roof surface area for a large scale photovoltaic system based on land uses, population, and building densities. The critical point is to estimate available roof surface in the existing buildings [9]. Types and configurations of PV cells installed on building affect the electricity production. As reported by Yoon, *et al.*, transparent amorphous silicon thin film can be utilized as window of buildings to expand the receiving area. Improvement on building design can increases the electric generation significantly, up to 47% [10]. Choi, *et al.*, explored PV analyst in the ArcGIS software, shows a correlation between usable roof top and PV electricity production in urban area [11]. Shading on roof top, which is common in urban area, can dramatically reduce the usable roof-top area. In addition, air pollution, high air temperature, and slow wind speed in urban area have been noticed to dim solar radiation [12]. A place-specific study is therefore needed to estimate the available rooftop solar energy.

In Indonesia, the data on solar irradiations over several big cities *e.g.* Jakarta, Semarang, Surabaya, and Denpasar have been collected [13,14]. The average daily global and diffuse radiations were recorded to 450 and 200 $cal.cm^{-2}$ day^{-1} in Jakarta, respectively. Meanwhile, the daily peak of 800 $W.m^{2}$ can be obtained in Surabaya. Despite its potential, study on the usage of urban-area roof top in Indonesia to provide solar hydrogen for FC-powered vehicles is unavailable. The present study is therefore aimed to estimate the potency of urban roof-top generation of solar hydrogen. In this case, Bandung city of Indonesia is chosen as the representative urban area. We proposed a web-like micro-grid connected PV system to support a hydrogen fuel station system.

MATERIALS AND METHODOLOGY

Polycrystalline solar panels of 100 W_p (Solarland SLP 100-12, China) were installed on rooftop and positioned at different inclinations and directions. Definition of inclination of the panel refers to tilt angle in a reference [15]. A horizontal-positioned solar panel was set as reference. Daily output voltage and current of panels were collected from the system of the solar panel with resistors as represent of the electrolyser resistance. A tailor-made logging system was utilized to record the voltage, current, and weather condition i.e. temperature and humidity. Meanwhile, solar intensity was obtained from Indonesian Agency of Meteorology, Climatology and Geophysics in Bandung. Solar-to-hydrogen efficiency was calculated based on a reference [16], where the efficiency is PV efficiency time electrolysis efficiency.

Available area of rooftop was estimated based on aerial view available in Google maps. The theoretical hydrogen production per area of available rooftop in various inclinations and directions were calculated based on Faraday equation. As validation, PEM electrolyser (Horizon Fuel Cell Technologies FCSU-010, Singapore) was installed on the panel-electrolyser system to estimate the actual hydrogen production from available rooftop area.

Experimental data was collected during period of January-April 2016, where the monthly sunhours is the shortest (less than 200 hours) along a year due to rainy season. Therefore, the result is expected as the lowest available solar energy. Estimation of available solar hydrogen was conducted based on solar panel orientation on rooftop. Fig. 1 shows experimental set-up.

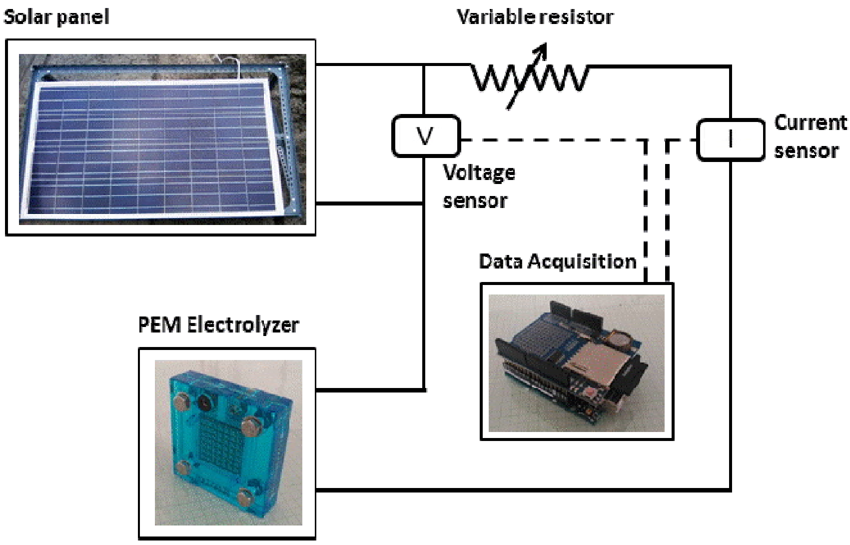


Fig. 1 Schematic Diagram of Experimental Set-up

RESULTS AND DISCUSSIONS

As the third largest city in Indonesia, Bandung is populated by more than 2.3 million people. It is estimated that more than 90% of its 168.23 km^2 landscape are the housing space, which is suitable for solar rooftop. Geographically situated at 2,460 feet above sea level and surrounded by mountains, the weather in Bandung is dominated by tropical highland rainforest monsoon climate. The average daily temperature, rainfall, and rainy days are 23.5^oC, 223.45 mm, and 20 days consecutively [17,18].

The current-potential (I-V) curve was obtained from measurement of current at various loads. Based on the curve, maximum output power (P_{max}) generated by the solar panel is 23 W, which is much lower than available peak power of 100 Wp.

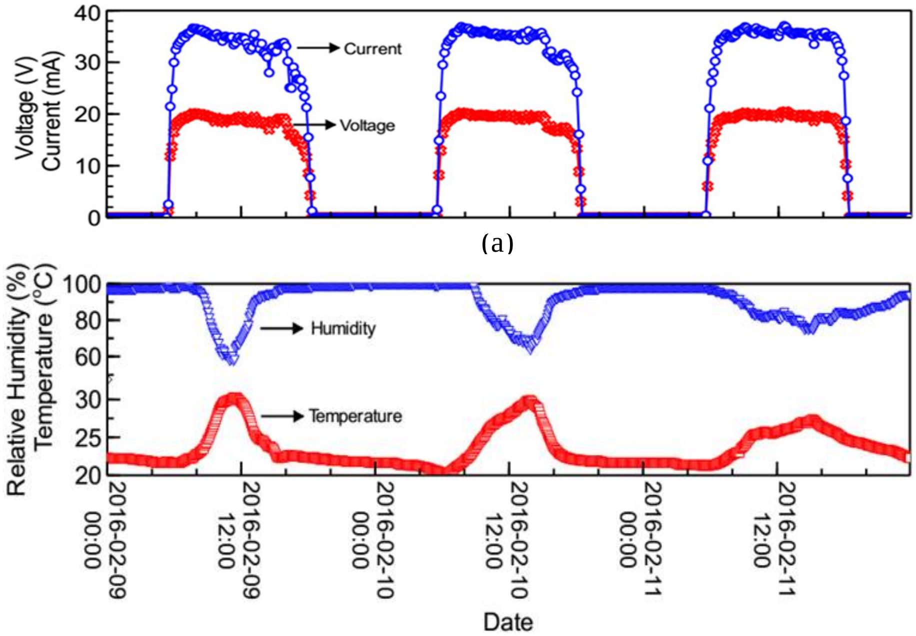
This condition was caused by low solar intensity of around 200 $W.m^{-2}$. Meanwhile, the watt peak (Wp) is measured at intensity of 1000 $W.m^{-2}$. With panel area of 0.85 m^2, efficiency of the solar panel is calculated at 10.27%. It is expected that surface temperature of the solar panel which is higher than standard of 25^oC (atmosphere temperature was recorded at around 30^oC) decreases the panel efficiency from manufacture specification of 12%.

Effects of panel inclination and orientation

The inclination of solar panel in our experiment was set at tilt angle of 30^o, following typical tilt angle of housing rooftop in Bandung. Handoyo *et al.* reported optimal tilt angle for solar insolation in Surabaya is at range of 0^o – 40^o [14]. With slightly different latitude (6^{o}55' S vs. 7^{o}15' S), the tilt angle of rooftop in Bandung is expected to satisfy those optimal range. Additionally, experiment at tilt angle of 45^o was conducted to represent several old buildings which were designed at that higher exceptional slope. A flat panel (tilt angle of 0^o) was installed along the variation on tilt angle and orientation (surface azimuth angle), which use also as reference. The reference is useful to minimize effect of daily weather fluctuation on the observed data.

Typical daily voltage-current output at load of 550 Ω, temperature, and humidity shown in Fig. 2 were collected using tailor-made data acquisition (DAQ) system. The load represents resistance of electrolyzer. The DAQ data of voltage and current were validated to commercial multimeter. We found that cloud is able to decrease significantly the panel voltage up to 25% (from 20 V to 15 V). Electrolyzer system requires voltage stability to maintain the electrolysis reaction. Therefore, design of electrolyzer should consider the voltage fluctuation, especially in the direct-electrolyzer (i.e. without DC-DC converter).

Effects of solar panel inclination and orientation on produced electricity are presented in Table 1. We found that electricity produced by the inclined panel compared to the horizontal one vary from 99.2% to 104.2%. During experiment in January to April, the sun is located in southern hemisphere. Counter intuitive to solar irradiation intensity, south faced panels seems produce lower electricity than horizontal one, despite its insignificant difference of 0.3% to 0.8%. The intensity, south faced panels seems produce lower electricity than horizontal one, despite its insignificant difference of 0.3% to 0.8%. The higher irradiation is suspected to increase panel surface temperature and reduces conversion efficiency of solar energy to electricity.



(b)

Fig. 2 Typical Daily (a) Voltage and Current Output of Panel with 550 Ω load (example of North faced, inclination of 30°), (b) Temperature and Humidity Profiles.

Solar Hydrogen Production using the PV-Electrolyzer System

Water electrolysis reaction in the PEM electrolyzer with 0.15 M KOH follows Equations (1) to (3). Thermodynamically, the reactions start at standard potential of 1.23 V. Due to the activation, ohmic, and polarization overpotentials, the operating voltage of the PEM electrolyzer is higher, in range of 1.8 to 3 V [17].

Cathode : $2\,H^+ + 2\,e^- \rightarrow H_2$ 0 V/SHE..(1)
Anode : $H_2O \rightarrow 2\,H^+ + ½\,O_2 + 2e^-$ 1.23V/SHE..(2)
Total : $H_2O \rightarrow H_2 + ½\,O_2$ -1.23V..(3)

Table 1 Effect of Inclination and Orientation of Solar Panel on Produced Electricity

Orientation	Inclination	Produced Electricity* (Wh/panel/day)	Ratio to Horizontal Panel
North	30°	6.65 ± 0.07	1.042
	45°	7.39 ± 0.08	1.010
South	30°	7.67 ± 0.07	0.997
	45°	7.72 ± 0.06	0.992
East	30°	7.90 ± 0.06	1.004
	45°	7.91 ± 0.07	1.042
West	30°	7.68 ± 0.06	1.010
	45°	7.62 ± 0.05	1.028

Note: * Estimated based on 550 Ω loads

The solar panel generates voltage at range of 18 - 20 V for about 10.5 (± 1.4) hours, while it changes drastically during sun rise and set (see Fig 3). There are two methods proposed for this situation where there are voltage difference between PV and electrolyser, i.e. indirect and direct systems. In the indirect system, the DC-DC converter is utilized to adjust panel voltage into the electrolyzer voltage. Meanwhile, direct system uses panel voltage without converter. As consequence, the cell is operated in high voltage when use monopolar configuration or we can use bipolar configuration to operate each cell in the common range of 1.8 - 3 V.

$$\eta_e = \frac{V_{H2,\ actual}}{V_{H2,\ theoretical}} = \frac{V_{H2,\ actual} . P.z.F}{I.t.R.T} \quad ...\ (4)$$

In our direct-system experiment, the produced hydrogen was collected using water filled burette. Efficiency of the electrolysis (η_e) is calculated based on Equation 4. The efficiency compares actual produced hydrogen ($V_{H2,actual}$) with theoretical one ($V_{H2,theoretical}$, ideal gas assumption). The $V_{H2,theoretical}$ depends on pressure (P), number of electron involved in reaction (z), electric current (I), time (t), and temperature (T). The symbols F and R are Faraday and ideal gas constants, consecutively. We found that the average efficiency of PEM electrolyzer is 82.79% with standard deviation of 9.91%. With efficiency of the solar panel of 10.27%, the total solar-to-hydrogen efficiency of the PV-PEM electrolyzer system is calculated at 8.5%. Gibson and Kelly reported hydrogen production efficiency of PV-PEM electrolyzer is 4.4 to 12.8% [16]. The results are mostly in range of 8 - 9%, where the realistic target is 10.5% [18]. Hence, our system is in satisfied configuration.

In this study, only rooftop area larger than 100 m^2 is accounted as feasible rooftop for panel installation (as illustrated in Fig 4). Area estimation using aerial view method is likely underestimate available rooftop area. In example for rooftop dimension of 10 m x 10 m, there are area differences of 50% and 29% for rooftop inclination of 30^o and 45^o. The differences are then assumed as unavailable rooftop area. As comparison, cities in Spain, Germany, Switzerland, and India have fraction of available rooftop in range of 22% to 95% [19].

Fuel stations in the north of Bandung (Dago area), the south (Kopo area), the west (Panghegar area) and the east (Panyileukan) were taken as sample of solar hydrogen generators location. Table 2 shows estimation of available rooftop area. Available rooftop area for solar panel installation around the fuel station within radius of 500 m is estimated based on Google Earth^{TM}. The rooftop is categorized into 5 classes based on its orientation, i.e. horizontal, north, south, east, and west faced rooftops.

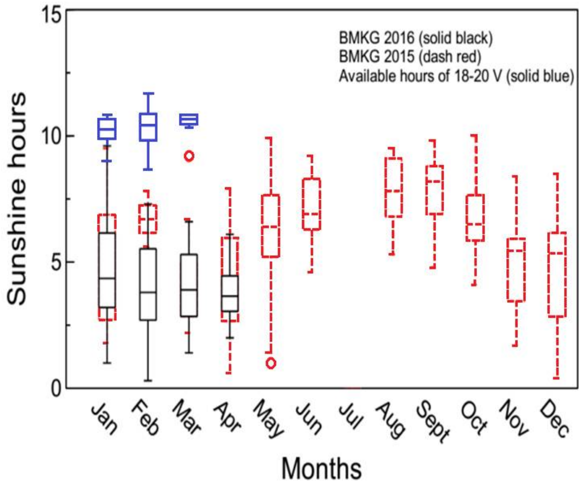


Fig. 3 Duration of Solar Panel producing voltage between 18-20 V (solid blue) compared with sunshine hours data (2015-2016) from BMKG (Indonesian Agency for Meteorology, Climatology and Geophysics)

Fig. 4 Typical rooftops in Bandung City, with potential available rooftops for installation of solar panels are marked using red line

Table 2 Available Rooftop Area within 500 m Radius around the Fuel Stations

Rooftop orientation	Available Area, m^2 *(% of total)*			
	North Region (Dago)	South Region (Kopo)	West Region (Panyileukan)	East Region (Panghegar)
North	31,780.01 *(29.71%)*	3,273.37 *(20.40%)*	9,743.99 *(36.07%)*	1,168.13 *(11.17%)*
South	23,025.29 *(21.53%)*	2,933.03 *(18.28%)*	8,046.07 *(29.79%)*	915.90 *(8.76%)*
East	19,786.43 *(18.50%)*	5,977.26 (37.24%)	7,697.68 *(28.50%)*	3,556.94 *(34.02%)*
West	10,904.69 *(10.20%)*	3,005.20 *(18.72%)*	1,524.3 *(5.64%)*	624.09 *(5.97%)*
Horizontal	21,455.00 *(20.06%)*	860.34 *(5.36%)*	NA	4,191.60 *(40.09%)*
Total	106,591.42 *(100.00%)*	16,049.20 *(100.00%)*	27,012.04 *(100.00%)*	10,456.66 *(100.00%)*

The Dago area provides the largest available rooftop. Meanwhile, other fuel stations have significantly lower available area for PV rooftop installation. Total production of solar hydrogen can be estimated from average production rate 7.57 Nm^3/day/panel and available rooftop area (refers to Tables 1 and 2). Thus, potency of solar hydrogen production for the north, south, east, and west areas of fuel stations are estimated at 15,132; 2,278; 3,834; and 1,484 $Nm^3.day^{-1}$, consecutively. This calculation is based on rooftop inclination and average system efficiency of 30° and 8.5%, respectively.

Hydrogen has lower heating value (LHV) of 290 Btu/ft^3 (at 32°F and 1 atm), which is lower than conventional gasoline of 15,518.97 Btu/ft^3 [20]. Recently, fuel cell vehicles have mile per gallon equivalent (MPGe) in range of 50-67 [21]. The MPGe measures average distance travelled per consumed energy by all-electric mode vehicles, where 1 MPGe equal to 0.013 $km.MJ^{-1}$. Taking vehicle storage of 40 L for driving range of 480 km, the requirement of hydrogen is estimated at 60.32 Nm^3. Thus, the produced solar hydrogen in Dago, Kopo, Panyileukan, and Panghegar Fuel Stations can provide fuel for about 250, 37, 63, and 24 vehicles per day, respectively.

Potency Mapping of Urban Solar Hydrogen Station in Bandung City

With decreasing on solar panel price in the recent years [22], the solar hydrogen system will become competitive option to support FC-powered vehicles. Assessed hydrogen supply system for FC buses in Spain, Vidueira, *et al.* reported that the grid-connected PV system gives lower installation and maintenance costs (€ 0.10 /Nm^3 H_2) than the direct grid-connected electrolyser (€ 0.72 /Nm^3 H_2) [7]. Compensate its higher installation and maintenance costs, the latter offers lower initial investment and short-term profitability. However, the grid-connected PV system provides potency on renewable energy utilization. Based on the situation, we propose web-like micro-grid connected PV-electrolyzer system as illustrated in Fig. 5.

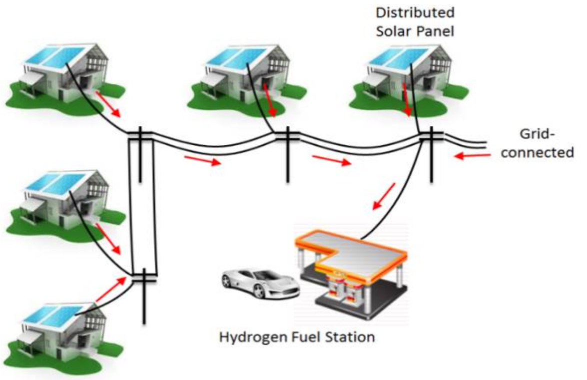


Fig. 5 Micro-grid connected PV system to support a hydrogen fuel station. The red arrows show electricity supply routes.

The micro-grid PV system will consist of existing fuel station equipped with solar hydrogen generator connected to grid and rooftop PV-installed housing. The public electrical grid (i.e. PLN in Indonesia) provides main source of electricity. Rooftop solar panels will provide the additional electricity.

We then categorize the Bandung City area based on potential available rooftop housing to analysis feasible location for solar hydrogen fuel station. The potency of solar hydrogen in Bandung City is mapped in Fig. 6, where the area is classified into 3 categories i.e. high, medium, and low, correspond to the feasibility of PV-PEM electrolyser microgrid installation (see Table 3). Based on the Fig. 6 and assuming that current existing gasoline fuel station will be equipped or transformed into hydrogen stations, there are 9.76% of the stations classified into high category, 41.46% into medium category and the rest (48.78%) are into low category. Recent vast development of west and east regions of Bandung City may increase feasibility of the area in the near future.

Table 3 Area Classification Based on Rooftop Coverage and Potency of Hydrogen Production

Classification	Potential rooftop area (m^2/area*)	Rooftop coverage (%)	Fuelling capability** (car/day)
High	> 50,000	> 20	> 110
Medium	12,500 – 50,000	5 - 20	30 - 110
Low	< 12,500	< 5	< 30

Note:
* Area is defined as 500 m x 500 m.
** Fuelling capability is based on consumption of 40 L gasoline or equal with 480 km driving range.

Total available rooftop for PV panels in Bandung city is estimated at 554.6 ha. With the average solar hydrogen production of 7.57 Nm^3/day/panel, potency for solar hydrogen production can reaches 4.85×10^7 Nm^3 per day. Sugiyono provided estimation on liquid fuel consumption for vehicles in Bandung recently up to 7.70×10^8 L (2015) and will increase to 1.66×10^9 L in 2030 [23]. In case of all available rooftop are installed with PV panel, energy from the produced solar hydrogen will equivalent with 199 times of that fuel consumption. The calculation assumes 365 operating days of the generation system.

The next challenges on solar hydrogen production are generation cost and storage. High quality of hydrogen from the electrolysis is suitable for fuel cell operation, despite the cost is still considered high. Strategy for reducing the cost is increasing efficiency, in example by removing DC-DC converter to simplify the PV-PEM system and matching the PV and electrolyser operating voltages [16]. Meanwhile, technology of hydrogen storage recently depends on high pressure storage at 250 bar [7] and metal hydride materials, e.g. magnesium or magnesium nickel hydrides. The recent research interests are aimed on finding a material which is capable to withstand hydrogen embrittlement under high pressure condition and a metal hydride with high hydrogen storage density.

CONCLUSIONS AND FUTURE WORKS

Throughout this paper, potency of rooftop solar hydrogen production in Bandung urban area for future electric vehicles application has been studied. The PV-Electrolyser system successfully provided solar to hydrogen conversion of 8.5%. Estimation of available rooftop using Google Maps application is considered as promising approach and possible to be used on other urban area.

The hydrogen station infrastructure is important for electric vehicles development. Therefore, further studies will be conducted to optimizing efficiency of hydrogen generator system, thus increase its economic feasibility. The compact PV-Electrolyser system with higher efficiency is in preparation stage to provide more data. Moreover, development of hydrogen storage is essential for supporting this solar hydrogen research.

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