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AN EVALUATION ON SOLAR POWERED HYDROGEN PRODUCTION

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ABSTRACT

Hydrogen is considered the lightest, simplest and most plentiful element in the universe. It can be a source of new, renewable and almost the cleanest fuel of the future. Also, solar energy has a significant share among renewable energy source. Especially photovoltaic power plants represent a good solution concerning electric energy supply. Turkey is looking for environment friendly renewable energy sources like most country. Photovoltaic power plants can be a sustainable energy source with huge potential for Turkey. Bursa province is located in the northwestern region and there are more efficient regions in terms of solar energy such as south region in Turkey. Soğuksu photovoltaic solar power plant is the first large scale power plant with 7 MW peak power in Bursa. In this study, generation values of a power plant were observed under actual operating conditions. The generation data showing the actual daily electricity generation values have been recorded in the library of the plant. This data has been used to investigation of daily hydrogen production performance of the power plant in theoretically. Proton Exchange Membrane (PEM) electrolyzer was selected for electrolysis of water. According to results, the maximum mass flow of hydrogen production can be 0.0625 $kgs^{-1}H_2$ for peak load and the electrolyzer can produce 1630 kg hydrogen in a clear summer day.

Keywords: Hydrogen production, PEM electrolyzer, solar energy, electricity generation,

1. INTRODUCTION

The future energy economy will consist of many diversified and combined renewable energy technologies [1]. Global warming and climate change bring renewable energy sources to the forefront. Nowadays energy from fossil fuels may be inexpensive but the solar energy with hydrogen technologies are essential components of a sustainable energy future. Fossil fuels are finite in nature and a major source of greenhouse gas emissions. Hydrogen which is one of the most powerful fuels can be extracted from steam reforming through the process of electrolysis and it can be used either for storing or generating electricity in power systems. Although every location on the Earth receives sunlight, the amount received varies greatly depending on geographical location. Turkey is one of the world's best areas for sunlight and the number of the photovoltaic installations has increased significantly in Turkey [2]. Solar energy is common value of the whole world among renewable energy sources but share of countries in solar energy differs. In the literature many countries have analyses based on solar energy. Kumar and Sudhakar [3] conducted a performance evaluation of a grid connected 10 MWp photovoltaic power plant in India. They pointed out that grid connected photovoltaic systems are the best choice among renewable energy sources.

Incekara and Ogulata [4] have studied on the electricity generation plan of Turkey and they reported solar energy will have the second place in Turkey's electricity generation within fifteen years until 2030. Some analyses have been prepared for cities of Turkey. Boran et al. [5] have suggested the best location for a photovoltaic system to be installed in Turkey and they have taken into account sun hour, solar radiation, mean temperature, and topography as evaluation criteria. The result of the analysis has indicated that Bodrum should be selected as the best site for installing grid connected photovoltaic power plant.

If hydrogen is to become the energy of the future, it must be produced using renewable energy sources and the technical and economic problems on its production, storage, transportation, and use should be solved. There are various methods used in hydrogen production [6]. Some studies have focused on the investigation of hydrogen production of a photovoltaic and thermal system. According to Cilogulları et al. [7] 0.018 kg hydrogen can be produced daily with 1.28 m^2 photovoltaic and thermal system. Water electrolysis is a hydrogen production technique that has reached the stage of industrial exploitation. Used with PV, it offers a sustainable mean for hydrogen production [8]. Likkasit et al. [9] have integrated solar energy into oil and gas industries to produce the hydrogen required in crude oil up grader processes. Pereira et al. [10] have analyzed the electricity generation through a mini hydro plant and a photovoltaic system particularly sized for a location in Portugal.

Proton Exchange Membrane (PEM) electrolyzer is good chosen for electrolysis of water. Yilmaz and Kanoglu [11] have thermodynamic evaluation of geothermal energy powered hydrogen production by PEM water electrolysis. In their study, energy capacity of the PEM electrolyzer is 3810 kW and mass flow rate of the produced hydrogen is 0.0340 kg/s.

Theoretically investigation of hydrogen production depends on actual electricity generation of the Soğuksu solar power plant has been presented in this study. The power plant is a photovoltaic and a grid connected type in the northwestern region of Turkey in the borders of Bursa province. It has started to electricity generation since 20^{th}March 2017. Soğuksu solar power plant is the first large scale plant in the Bursa province. This point makes it important because photovoltaic investments will increase in case of success of the power plant. Monthly global radiation values of the region are below the average in Turkey. This means the power plant is not a pretentious investment. The electricity generation is very low on autumn and winter seasons under the effect of overcast weather. The generation values of the power plant were observed under real weather conditions and hydrogen production depends on actual electricity generation were also calculated in this study. The data are the actual generation data recorded by the power plant library and transmitted to the grid. Daily total electricity generation with hydrogen production capacity was demonstrated.

The system which is investigated in this study is given in Figure 1 schematically. There are three main sections in the system. One of them is Soğuksu solar power plant where are necessary electricity is generated to produce hydrogen. The other section is solar collectors and water heater system. In this section the water will electrolyzed is preheated to 80 ºC before enter to PEM electrolyzer. The last section is PEM electrolyzer where hydrogen is produced. There are explanations in detail in the next paragraphs for the sections.

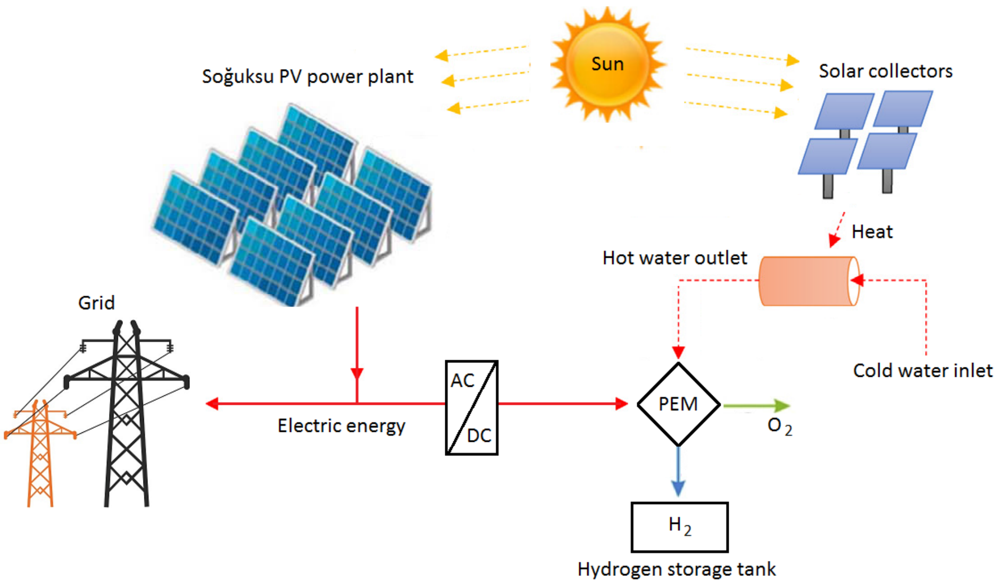

Figure 1. PV power plant aided hydrogen production system

2. MATERIAL AND METHODS

Soğuksu solar power plant is a large solar field including seven different power plants each has 1 MWp capacity. There are 20 inverters in each 1 MWp scale power plant and each inverter has 10 strings. The photovoltaic solar panels connected to strings in series. Each string has 22 panels. In the plant installation a single type of panel was preferred. The properties of the panel used in the power plant which taken from producer catalog are given in Table 1. The type of panels preferred in the plant is not the most efficient panel type in the market. The commercial outlook of the panels was influential in the selection of this type. Before installing of the power plant there are some processes must be taken in to account such as designing, constructing. Firstly, a suitable area and the financing are necessary like in every investment. Soğuksu solar power plant has all the necessary processes and legal permits.

Table 1. Properties of PV solar panels used in Soğuksu solar power plant

Model of the Panel	UP-M270P
Type	Polycrystalline Silicone
Power Rating	270 Watt
Peak Efficiency	16.6%
Number of Cells	60
Dimension of the Cells	156 mm X 156 mm
Length	1640 mm
Width	992 mm

Turkey government has some effective actions in terms of renewable energy. One of them is keep out of license the plants which is under 500 kW capacity. This condition also applies to solar power plants. But capacity of Soğuksu solar power plant is bigger than 500 kW so it can be accepted as big type power plant. The general characteristics of the power plant and its coordinates from satellite images are shown in Table 2.

Theoretically, the amount of generated electricity by a solar power plant is function of the panel surface area of the plant, the number of days it produces electricity, the panel and inverters efficiency used in the plant. Also, it is directly related to the energy carried by the sunrays coming onto the power plant panels.

Table 2. General characteristics of Soğuksu solar power plant

Area where the power plant is installed	170000 m^2
Number of panels used	30800
Total panel surface area	50108 m^2
Total cell surface area	44972.9 m^2
Plant Power	7 MWp
Inverter Efficiency	97 %
Generation Commencement Date	20 March 2017
Plant Coordinates	40º 12’ 57’’ N 29º 25’ 50’’ E

Soğuksu solar power plant is located within the boundaries of Bursa province. Its geographical location is next to Yenişehir plain. In Figure 2, the map shows the location of the power plant and its satellite image. In the power plants conditions, there is no cooling application is performed on the panels. The location of the power plant has the advantage of natural ventilation as it is situated on a high hill relative to the plains.

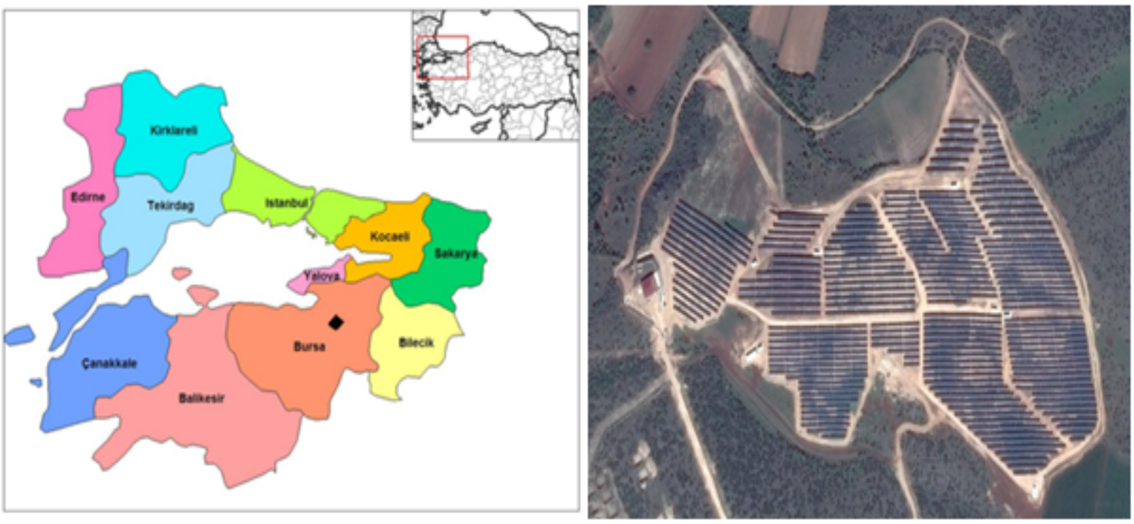

Figure 2. Location and satellite view of Soğuksu solar power plant

In hydrogen production system, the PEM electrolyzers are built around a proton conductive polymer electrolyte. The schematic of PEM electrolysis section for hydrogen production is shown in Figure 1. Different PEM electrolyzer models can be designed. In this study Yilmaz and Kanoglu’s [11] model was used. According to this model, hydrogen can be produced at a rate of 0.0340 kg/s by using 3810 kW electricity power. With right proportion, the produced hydrogen will be 0,054 kg/s by using 6 MW electricity power. This result has conformity with literature because Yuksel and Ozturk [12] have reported the same result. Liquid water is fed to the preheater at a reference environment and is heated by the used solar collectors. Electricity and preheated water are supplied to the PEM electrolysis to drive the electrochemical reactions.

Exiting from the cathode, produced H_2 (hydrogen) dissipates heat to the environment and cool down to the reference environment temperature.

Water which will be electrolyzed can inlet to PEM electrolyzer at any temperature. But water fed to the electrolyzer at higher temperature to increase the efficiency of the electrolyzer. There is no waste heat near of the Soğuksu power plant so there is three way to preheat the water. One of them is use electrical heater. This method is simple and easy but electrical heater will use %2 of the generated electricity approximately. The other method is using the water as coolant for solar panels. Efficiency of the panels and value of the generated electricity will increase as a result of this method. But the exact generated electricity value cannot be said without an extra analysis. In this study the data are the actual generation data recorded by the power plant library. The last method is use solar collectors to heat the water. This method was selected because it will not affect the generated electricity value. Soğuksu photovoltaic power plant has been established for electricity generation. The last phase of the electricity is AC before transmit to grid. Electrolyzers use the electricity in DC phase. There is added an extra AC-DC converter in the system as shown in Figure 1. This converter will cause decreasing on electricity value, it was neglected.

The system which is investigated in this study includes three main sections as before mentioned. Each section has mass and energy balance which can be defined with mathematical equations. As the first section, the instant electricity generated of the Soğuksu solar power plant can be defined with equation (1).

$$E_G = N_P E_S \eta_P \eta_{inv} \eta_{los} \tag{1}$$

In this equation, N_P is total panel number in the power plant and E_S is the incident solar radiation energy on the panels according to cell surface area. Also, η_{inv} is the inverter DC to AC conversion efficiency between 95% - 97%. It has specific value depend on each days and time. Cell surface area of the panels is lower than total panel area because of frame area. Also η_P, panel conversion efficiency can be defined in equation (2) where E_{el} is the generated electricity by panels.

$$\eta_P = \frac{E_{el}}{E_S} \tag{2}$$

There can be losses on electricity generation on photovoltaic power plants. The losses are usually caused by module mismatches, temperature effects, and dust or snow on the panels, conduction losses, wiring, humidity, wind speed, and soiling. η_{los} shows the total efficiency depend on the losses. In order to have more electricity produced by the photovoltaic power plants, the losses should be reduced to their lowest values. In this study, the presented actual electricity generation values are produced under the mentioned losses. Electrical properties of photovoltaic panels at standard test conditions (STC) can be defined with Eq. (3). Standard test conditions are 1000 W/m^2 solar irradiance and 25 °C cell temperature.

$$E_{el} = I_{dc} V_{dc} \tag{3}$$

where I_{dc} is current and V_{dc} is voltage of the panels in DC phase. Maximum voltage of the panels is given as 31.4 V in producer catalog at standard test conditions and also maximum current is 8.6 A.

The second section of the system is Proton Exchange Membrane (PEM) electrolyzer which works under some parameters such as voltage, current density, and temperature also flow rate in the electrolyzer. For Proton Exchange Membrane electrolyzers, the electrolyte is an acid polymer membrane made of Nafion. This membrane, acts also as gas separator. Water is decomposed into oxygen and hydroxonium ion (H_3O^+) in the anode. Hydroxonium ion migrates through the acid membrane to the cathode where hydrogen and water are formed. the valid temperature range is between 25 – 80 ºC and the current density range is between 0 – 10,000 A/m^2 [18]. The maximum operating temperature is of the order of 150 ºC and the operating current is usually higher than 1600 mA/cm^2. The efficiency could be as high as 70% [16]. Mass and energy balance of the Proton Exchange Membrane electrolyzer can be defined under some assumptions that all gases involved are ideal gases and any side reaction or mixing is neglected. Electrolysis of water as an electrochemical process operating at constant pressure and temperature, the maximum possible useful work is equal to the change in Gibbs energy. Theoretically, the energy required for water electrolysis is given by the change in the enthalpy of reaction ΔH . The global reaction during water electrolysis is:

$$H_2O \rightarrow H_2(gas) + \frac{1}{2}O_2(gas) \tag{4}$$

Water is in the liquid state and according to the thermodynamic laws, the theoretical energy necessary for this reaction to take place is given by:

$$\Delta H = \Delta G + T\Delta S \tag{5}$$

where ΔG is the required electrical energy and $T\Delta S$ is the thermal energy demand. ΔG represents the reversible part of the process while $T\Delta S$ represents the irreversible part of the process. Also the electricity energy of involved in the Proton Exchange Membrane electrolysis operation can be determined by the following electrochemical model as:

$$\dot{W}_{electricity} = I_e V_e \tag{6}$$

where V_e is the necessary cell voltage for the startup of electrolysis operation. I_e is the current density and $\dot{W}_{electricity}$ is the electrical power consumption in electrolysis.

The last section is solar aided water preheater system with solar collectors. The thermal energy equation of the solar collectors as follows:

$$\dot{E}_{th} = \dot{m}_w c_p (T_{out} - T_{in}) \tag{7}$$

where $\dot{m}_w$ is the water mass flow, c_p is the specific heat of the water. T_{out} and T_{in} are the output and input water temperature, respectively.

3. RESULTS AND DISCUSSION

According to solar potential map, the northwestern Anatolia region is not among the most sun-soaked regions of Turkey. But Bursa province is in this region with Soğuksu photovoltaic power plant. Especially in winter, the effect of cloudy and overcast weather on the electricity generation of the power plant is significant. Generated electricity values by Soğuksu solar power plant was presented to literature [13]. A summer day with clear skies can be described as the perfect day for a power plant. Figure 3 shows the changes in daily electricity generation with hydrogen production capacity on a clear day at the power plant.

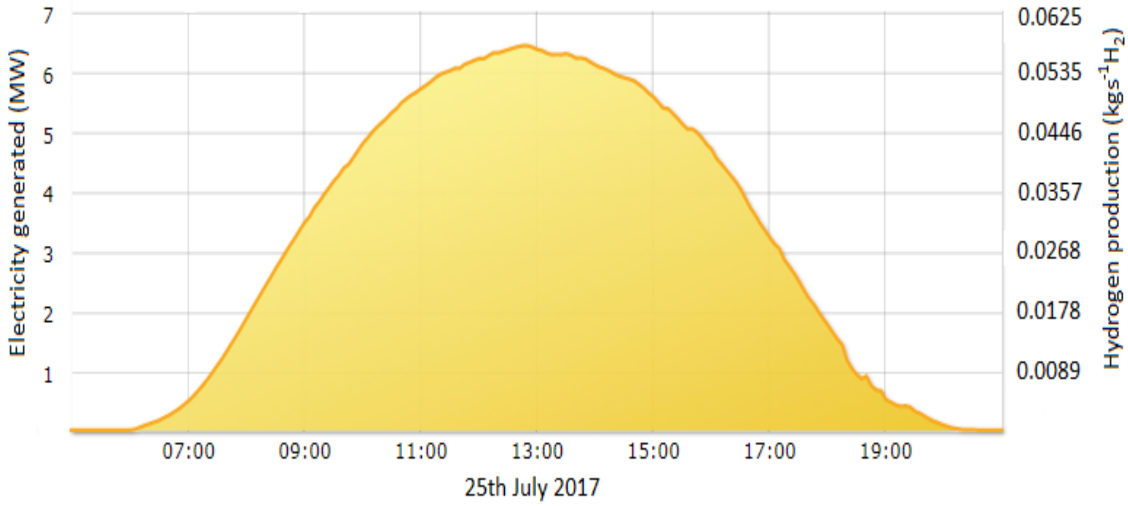

Figure 3. Distribution of the generated electricity with hydrogen production capacity in Soğuksu solar power plant on a clear summer day

In the distribution given above, the electricity generated in the power plant on July 25, 2017 is shown. Behavior of the graph is very close to a perfect day. The power plant started to wake up after 6:00 am in the morning. Before 13:00, the peak generation power reaches about 6.5 MW. The electrolyzer can produce 0.06 kg/s hydrogen for this loading approximately. Electricity generation continuing until 20:00 reached a total value of 50.74 MWh throughout the day. In terms of hydrogen production, the electrolyzer can produce 1630 kg hydrogen in this day.

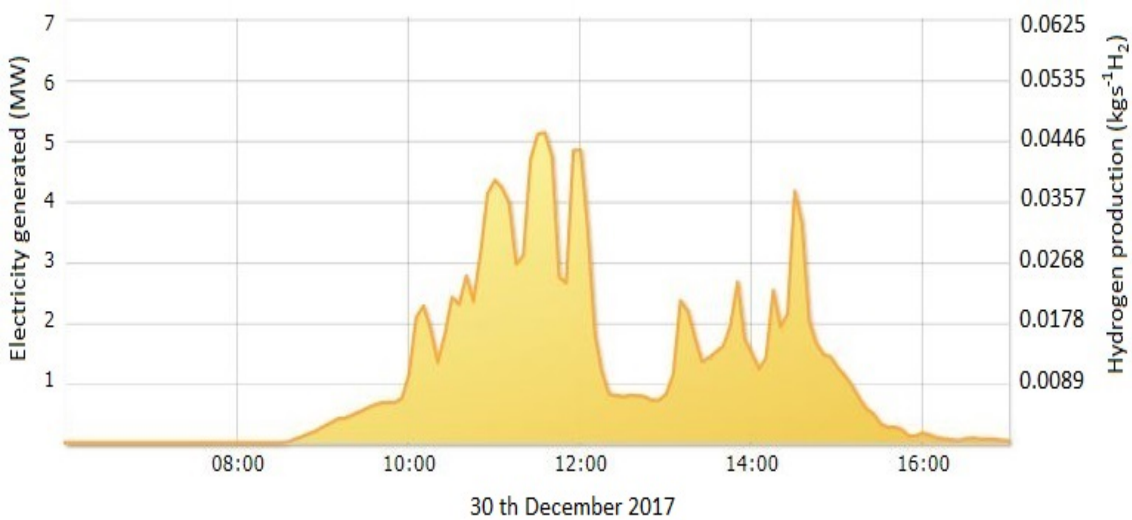

Figure 4. Effect of overcast weather on electricity generation and hydrogen production distribution in Soğuksu solar power plant

The generation distribution given in Figure 3 is an expectation. It is not always possible to talk about such a generation capacity especially in winter days. The daily generation distribution with hydrogen production capacity of a day that can be interpreted as a bad day is given in the Figure 4. The figure shows the effect of overcast weather on electricity generation distribution through a day. The generation values given in the figure belong to December30, 2017. The weather conditions have significantly affected on electricity generation and hydrogen production. The fluctuations in electricity generation can be easily seen on the figure. 12.74 MWh of electricity was produced throughout the day and worse days were experienced during the period evaluated in this study. In terms of hydrogen production, the electrolyzer can produce 410 kg hydrogen in this day approximately. Total hydrogen production will be revealed depending on the number of days with clear and overcast weather.

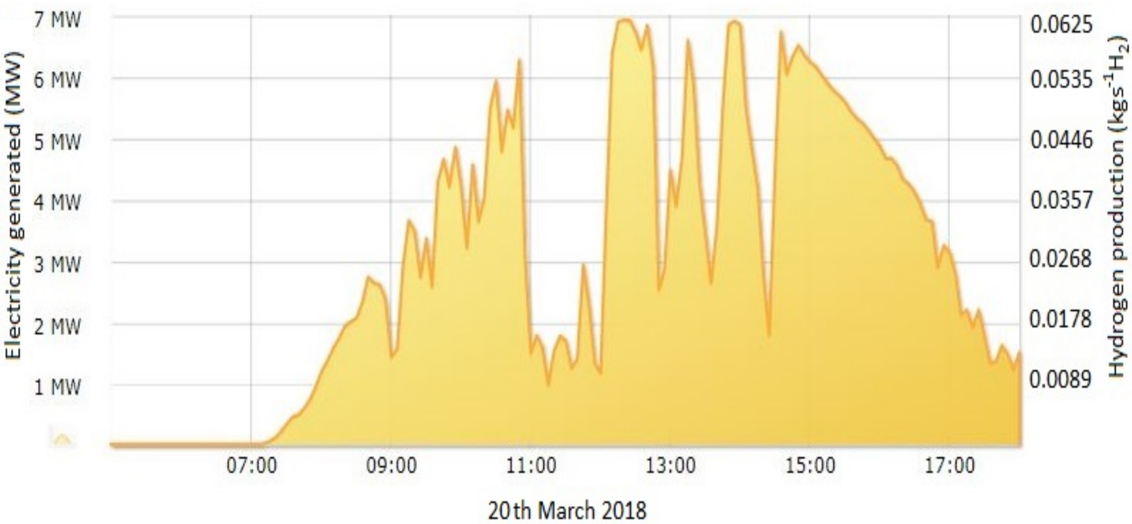

Figure 5. Distribution of the generated electricity with hydrogen production capacity in Soğuksu solar power plant with peak load

Figure 5 shows some instants that peak load is generated. The electrolyzer can produce 0.0625 kg/s hydrogen for peak loading. The perfect day which has peak load was not observed. Actually, number of perfect days is very low so it is normal that both of them were not observed together. The generation values given in the figure belong to March20, 2018. 36.74 MWh of electricity was produced throughout the day. The capacity of the electrolyzer can be 1180.3 kg hydrogen production approximately. Finally, a very bad day will be showed from winter.

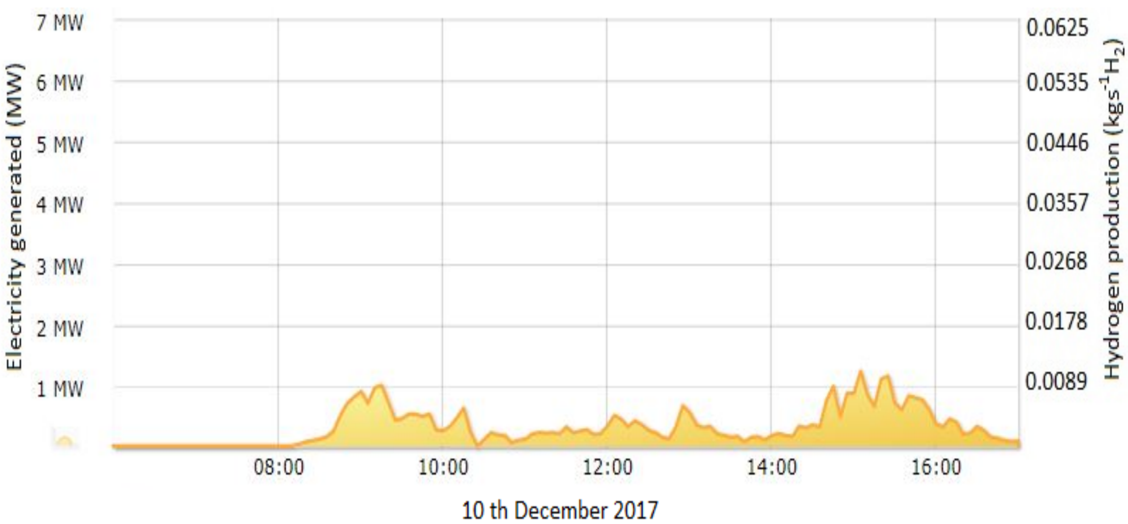

Figure 6. Distribution of the generated electricity with hydrogen production capacity in Soğuksu solar power plant on a winter day

Figure 6 shows distribution of the generated electricity with hydrogen production capacity in Soğuksu solar power plant on a winter day. The day is one of the bad days in terms of electricity generation. The generation values given in the figure belong to December10, 2017. 3.39 MWh of electricity was produced throughout the day. The electrolyzer can produce 108.9 kg hydrogen in this day.

4. CONCLUSIONS

In this study, daily hydrogen production capacity depends on electricity generation of a photovoltaic grid connected solar power plant with 7 MWp installed power located in the north west of Turkey was performed. The power plant is the first solar power plant installed in the region in this scale. It has 30800 panels each generating 270 W of electricity. Daily electricity generation values of a power plant were observed under actual operating conditions and recorded in the library of the plant. This data was used to investigation of daily hydrogen production capacity of the power plant in theoretically. Proton Exchange Membrane (PEM) electrolyzer was selected for electrolysis of water. According to results, the maximum mass flow of hydrogen production can be 0.0625 $kgs^{-1}H_2$ for peak load and the electrolyzer can produce 1630 kg hydrogen in a clear summer day.

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