STORING SOLAR ENERGY IN HYDROGEN

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ABSTRACT

Using solar energy in photovoltaic power plants is an important method of electricity generation from renewable energy sources. Its potential is vast and technically easy to utilise. The rapid development of photovoltaic sources is having a negative effect on the electric power system control. One option for mitigating this effect is to store the energy generated by photovoltaic in times of excess power in the grid and supply it to the grid when required, i.e., during peak periods of the daily load curve. Photovoltaic power plants in connexion with a hydrogen storage system seems very promising as a sources of electric power in an island (off-grid) systems. This paper describes our research into solar energy storage using hydrogen technologies in the case of off-grid systems. Storage in hydrogen as an energy carrier is currently the focus of intensive research in many research centres.

Keywords: *storage, solar energy, hydrogen, efficiency, electrolyzer mode*

1. INTRODUCTION

Solar radiation strikes the Earth's surface unevenly and its intensity depends on the season, time of the day, and local weather conditions. As far as utilisation of solar radiation for production of electric power by means of photovoltaic power plants is concerned, the process usually occurs upon request from the linked electric power system regarding supply of power at minimum or zero level. To eliminate negative impacts on operation of electric power networks due to unsolicited supply of power, the power output needs to be limited by certain means. Should the desired solution not include non-economical disconnection of photovoltaic power plants from the network, the power generated by these as excessive at the certain moment must be stored. One of the options, which is still undergoing the research stage, deals with storage featuring hydrogen technologies.

Besides the description of laboratory system for storage of electric power into hydrogen built in our facility, this paper deals with further analysis of data obtained through operation of the system. Attention is paid mainly to the issue of efficiency of hydrogen production using electrolysis of water and potential means for its improvement. The existing operation of this system has revealed that the weakest link used in the system is the hydrogen generator: low-temperature electrolyzer of PEM type. Research in the field of electrolytic production of hydrogen and its subsequent utilisation in fuel cells will be soon supported by launching the new laboratory of hydrogen technologies, which is being built within the Technological Centre Ostrava.

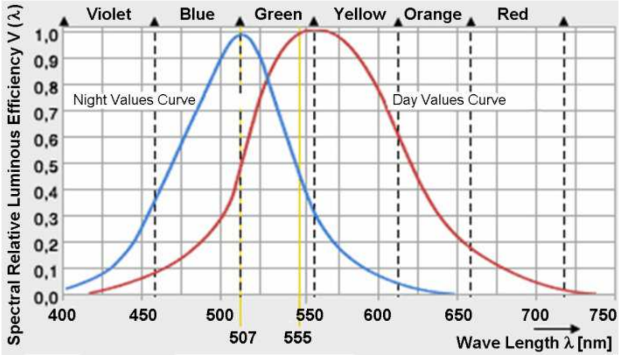

Fig. 1 Spectral curve

2. SOLAR ENERGY

From the environmental point of view, solar energy is the most environment-friendly and cleanest source of heat and electric power. The efficiency of conversion of solar radiation into electric power per one metre of active surface reaches the level corresponding with 110 kWh of electric power per year, using contemporary photovoltaic systems. The total period of sunshine and clear skies in the territory of Czech Republic ranges between 1,400 and 1,700 hrs./year. Photovoltaic panels produce electric power even when the Sun is obscured by clouds. However, the total production represents just a fraction of actual capacity under ideal conditions. Peak output of photovoltaic panels is achieved around 12 a.m., when the radiation intensity reaches it top level. [1]

The spectrum of solar radiation is formed by the infra-red (heat), visible and ultraviolet radiation (see Fig. 1). Solar facilities help us make use of heat energy directly or convert the solar radiation energy into electric power.

2.1. Photovoltaic Power Plant Principle

Energy can be gained from the Sun directly or via indirect conversion using solar collectors or by means of direct conversion using semi-conductor photovoltaic panels.

The indirect conversion involves extraction of heat using solar collectors. The collectors are situated around the focus comprising thermal calls that serve to convert heat into electric power. Thermal-electric conversion is based on the principle of Seebeck effect. Difference in temperature within a connection circuit with two conductors made from different material each results in generation of electric power. That is a thermal-electric cell. Characteristics and efficiency of the cell depend on properties of both metals in both conductors and the difference in temperatures between hot and cold junction respectively. An assembly of conveniently linked thermal-electric cells form a thermal-electric generator.

The direct conversion process makes use of photovoltaic effect with release of electrons within a specific substance driven by light. That happens in certain semi-conductors (silicon, germanium, cadmium sulphide, etc.). A photovoltaic cell comprises a thin mono- or poly-crystalline silicon plate, which is enriched with atoms of trivalent element (e.g. boron) on one side and atoms of pentavalent element (e.g. arsenic) on another. Once the plate is hit by photon, negative electrons will be released and "holes" with positive charge will be left behind. If both sides of the plate touch electrodes linked with a conductor, the electric current will pass through. One cm^2 of solar cells produces approx. 12 mA of electric current. One m^2 may produce up to 150 A of direct current around noon during summer days. Serial-parallel connection of cell forms a photovoltaic panel. [1]

3. FUEL CELLS LABORATORY AT VSB - TU OSTRAVA

The fuel cells laboratory at VSB - TU Ostrava is utilised for research of hydrogen technologies and their application in practice. The laboratory is full equipped with a complete hydrogen plant and lines for distribution of hydrogen and nitrogen, which is used as a safety gas here. Hydrogen is stored both in pressure vessels as well as containers and metal-hydrides are stocked in form of La/Ce-Ni alloy material.

The laboratory is equipped with two hydrogen generators, specifically low-temperature electrolyzers Hogen GC600 (see Fig. 2) and two modules type low-temperature fuel cells NEXA Power Module Ballard. Both types of equipment use the PEM (Proton Exchange Membrane) technology. These devices are fitted into ventilated exhaust hoods with safety sensors for hydrogen leaks detection installed in the entire laboratory. Electrolyzers can be powered either from the mains with 230 V or connected into the laboratory island type system used for storage of electric power from solar radiation into hydrogen. For this purpose, the laboratory roof is installed with poly-crystalline photovoltaic panels Schott Poly 165 with the total installed capacity of 1,980 Wp.

The power storage system also comprises semi-conductor converters Sunny Charger 40, Sunny Island 4248 and SD-1000 as well as four lead batteries Fiamm 12FLB300 defining the voltage on direct bus (48 V). Demineralised water required for production of hydrogen in electrolyzer is prepared in the osmotic filtration unit Demiwa 10 Rosa.

Measuring of electric and non-electric values in the laboratory is conducted by means of measurement system comprising measuring sensors with signal transmission and evaluation by means of two measurement cards NI USB-6218 for processing on two PC. The power storage system is controlled by PLC automatic programmable units Siemens SIMATIC.

Fig. 2 Hogen GC 600 Electrolyzer

3.1. Devices in Hydrogen Production System

The hydrogen production system consist of electrolyzer and pressure vessels.

3.1.1. Electrolyzer

Electrolyzer ensures the process or electrolytic decomposition of demineralised water to produce hydrogen and oxygen. Each electrolyzer is powered from a renewable energy source, therefore the production of oxygen does not create any harmful emissions (CO_2, SO_2, NO_x). For Hogen GC600 electrolyzer parameters see Table 1. The electrolyte used here is the firm PEM membrane (thickness < 1 mm). Porous electrode layers are applied to both sides of the membrane. Passing of current is ensured by means of ion H_3O^+ on cathode or OH^- on anode. Electrochemical reactions on electrodes:

- Anode: $2\,H_2O \rightarrow 4\,H^+ + 4\,e^- + O_2$

- Cathode: $4\,H^+ + 4\,e^- \rightarrow 2\,H_2$

- Overall: $2\,H_2O \rightarrow 2\,H_2 + O_2$

Table 1 The parameters of Hogen GC600 electrolyzer

Maximum Hydrogen Flow Rate	0 - 600 cm^3 / min
Delivery Pressure	300 - 1,379 kPa
Hydrogen purity	99.9999 %
Contained Hydrogen Inventory	1.9 l – Full Level to Shutoff Level
Water Tank Duration (full to shutoff)	>100 Hours of Continuous Full Rate Operation
	>50 Hours of Continuous Full Rate Operation
Power Consumption	< 1,200 W

3.1.2. Pressure vessels

Pressure vessels are used or storage of larger amounts of hydrogen (see Fig. 3). These vessels feature layered laminated walls. The internal wall layer is made from stainless steel to resist effects of pressure hydrogen. Hydrogen is normally stored and distributed in pressure vessels at 20 to 35 MPa. The use of pressure electrolyzers does not require any compression unit, as the gas is being compressed right inside the electrolyzer.

Fig. 3 Packs of pressure vessels

Table 2 Parameters of pressure vessel

Water volume	50 litres
Volume of hydrogen in storage at the pressure of 20 MPa	9,000 litres
Volume of hydrogen in storage at the pressure of 1,380 kPa	620 litres

4. ELECTROLYSIS OF WATER AND ITS PRINCIPLES

Electrolysis of water is a process with hydrogen released on cathode and oxygen released on anode respectively. The process involves consumption of water and electric power. Due to low conductivity of water, the medium used is water solution of electrolyte with high conductivity. Electrolysis takes place under atmospheric pressure conditions, producing double the amount of hydrogen than oxygen. The Faraday's law implies the following relations for amounts of oxygen and hydrogen produced:

$$M_{H_2} = \frac{I \cdot t}{2 \cdot F} \quad ; \quad M_{O_2} = \frac{I \cdot t}{2 \cdot F} \qquad (1), (2)$$

where:
M_{H2} – molar mass of hydrogen ($kg \cdot mol^{-1}$)
M_{O2} – molar mass of oxygen ($kg \cdot mol^{-1}$)
I – current flowing through electrolyzer (A)
T – duration of electrolysis (s)
F – Faraday's constant ($F = 9.648 \cdot 10^4\ C \cdot mol^{-1}$)

that implies the following for amount of hydrogen and oxygen obtained:

$$m_{H_2} = \frac{I \cdot t \cdot M_{H_2}}{2 \cdot F} \quad ; \quad m_{O_2} = \frac{I \cdot t \cdot M_{O_2}}{4 \cdot F} \qquad (3), (4)$$

The minimum amount of energy required for decomposition of 1 mol of water is determined by the value of ΔG, whereas the formula below applies:

$$\Delta G = 2 \cdot U_{rov} \cdot F \qquad (5)$$

where: U_{rov} ….balanced voltage on the oxygen-hydrogen cell, when reactions in both directions occur at the same rate.

The voltage at 25 °C (298 K) can be expressed in figures as follows:

$$U_{rov} = \frac{\Delta G_{25°C}}{2 \cdot F} = \frac{237{,}000}{2 \cdot 9.648 \cdot 10^4} = 1{,}228 \quad V \qquad (6)$$

The equilibrium potential will enable production of much larger volume of hydrogen over a certain period of time, compared to low level of equilibrium potential, yet it will reduce the efficiency of electrolyzer. Production of larger volume of hydrogen requires increase of cell potential. That will help overcome the resistance of gas release on electrodes, the so called activated electrode potential, and ohmic resistance of cells. [2]

Consumption of electric power can be reduced by adding heat to the reaction. Heat is cheaper than electric power and increased temperature even improves the efficiency of electrolysis. The reaction requires minimum potential of 1.228 V at 25 °C (298 K). Heat must be supplied from ambient source. Increase of potential to 1.47 V at the same temperature of 25 °C (298 K) results in increase of temperature in reaction, so there is no need for additional heat supply. Further increase in potential will not result in any electrolysis efficiency improvements. [2]

5. LABORATORY MEASUREMENT

The electric power for production of hydrogen in electrolyzer was supplied from solar panels (see Fig. 4). The block diagram below (see Fig. 5) shows linkage of individual parts of the system, including measurement points. All the power from photovoltaic panels was intended for production of hydrogen. The load on alternating current bus was not connected and the accumulator bank was fully charged.

Table 3 The parameters of photovoltaic panels

Type	Schott Poly 165
Nominal power (Wp)	≥165
Voltage at nominal power (V)	35.10
Current at nominal power (A)	4.70
Open - circuit voltage (V)	43.60
Short - circuit current (A)	5.27
Module efficiency level (%)	12.60

Fig. 4 Photovoltaic panels situated on the laboratory roof

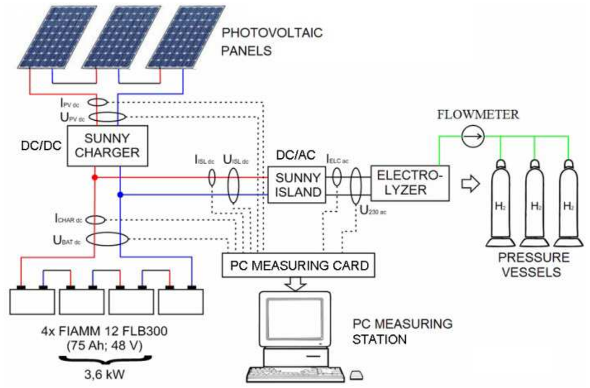

Fig. 5 Block diagram of the system measured [3]

Individual measurements were taken within specific time intervals of 0 - 60 minutes. Assessment of correct and comparable results was conducted using final values of monitored parameters only, measured within the time interval of 60 minutes. During measurement, the electrolyzer control panel was used to change pressure of hydrogen produced within two threshold values (300 kPa - 1,379 kPa). The minimum and maximum thresholds for hydrogen pressure were matched by measurements following the change to another vital input parameter: the temperature of reaction water. The values involved were threshold limits again, as these could be set with respect to operational safety for prevention of damage to the ion exchanger membrane inside. Measurement were taken at the temperature of 5 °C (cold water) and 45 °C (hot water).

Table 4 Results of laboratory measurements

Electrolyzer mode	E_{SV} (Wh)	V_{H2} (l)	E_{H2} (Wh)	Hydrogen pressure increase (kPa)	Efficiency (%)
T_{water} = 45 °C, p_{H2} =1,379 kPa	396	40.53	119.20	28	30.10
T_{water} = 5 °C, p_{H2} =1,379 kPa	458	40.05	117.80	21	25.72
T_{water} = 45 °C, p_{H2} = 300 kPa	375	40.12	118.00	34	31.47
T_{water} = 5 °C, p_{H2} = 300 kPa	397	32.41	95.32	21	24.01

E_{SV} - Electric energy consumed by the electrolyzer
V_{H2} - Amount of hydrogen produced
E_{H2} - Equivalent amount of energy in hydrogen produced

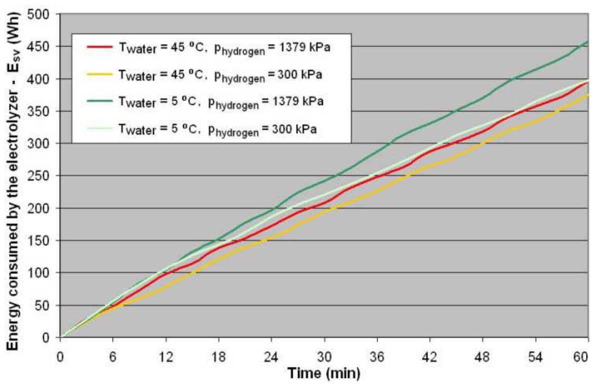

Fig. 6 Time dependence of energy consumed by the electrolyzer

Measurement results and values of set parameters have been included in Table 4. Figures 6, 7 and 8 show the time dependences of measured values.

6. CONCLUSIONS

The laboratory measurement described in this paper was conducted during production of hydrogen using the electrolyzer Hogen GC600 to help us determine the most convenient settings of electrolyzer parameters. The measurement was associated with a change to the vital input parameter of electrolytic production of hydrogen - the reaction water temperature. The measurement was aimed at both threshold values of potential settings for hydrogen pressure on electrolyzer, i.e. the minimum and maximum values (300 - 1,379 kPa). The main issue during this measurement was to keep the temperature of reaction water at the best constant value possible, which was achieved for both cold and hot water, with tolerance of ± 0.5 °C. The best results obtained through the measurement were based on the electrolyzer mode with minimum hydrogen pressure and hot reaction water with 375 Wh of electric power consumed and the electrolyzer efficiency calculated as 31.47 %. On the contrary, the worst results were shown by electrolyzer mode with minimum hydrogen pressure and cold water, consuming 397 Wh of electric power, which is not the highest power consumption figure, yet the electrolyzer efficiency was at its lowest (26.21 %). The above mentioned findings were then implemented as basis for operational optimisation of the whole hydrogen storage system, the most important part of which is the electrolyzer subject to examination.

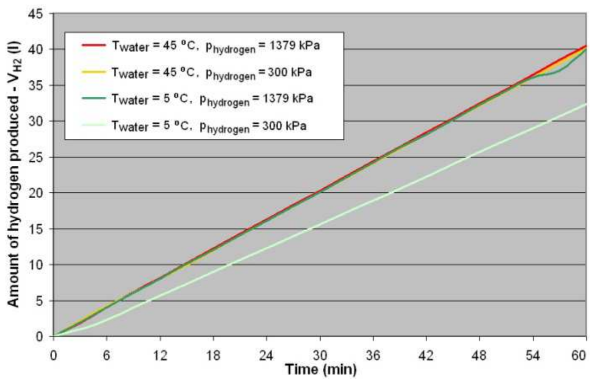

Fig. 7 Time dependence of amount of hydrogen produced

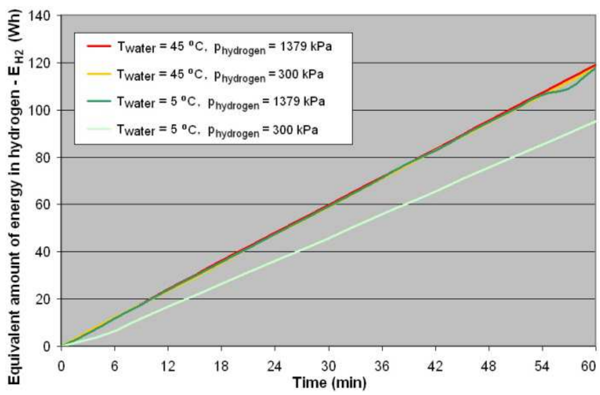

Fig. 8 Time dependence of equivalent amount of energy in hydrogen produced

ACKNOWLEDGMENTS

This work was supported by the project ENET - Research and Development for Innovations Operational Programme No. CZ.1.05/2.1.00/03.0069, by the Czech Science Foundation - No. GAČR 102/09/1842, and by the Ministry of Education, Youth and Sports of the Czech Republic (No. SP2013/137).

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Received September 10, 2013 , accepted September 28, 2013

BIOGRAPHIES

Jan VACULIK was born in 1986. He received the MSc. degree in Electrical power engineering from the VSB - Technical university of Ostrava in 2010, Czech Republic. Since 2011 he is a Ph.D. student in Department of electrical power engineering, in the same university. His main fields of interest include Renewable energy sources and Hydrogen based devices.

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Daniel MINARIK was born in Chrudim, Czechoslovakia, in 1982, graduated from the Faculty of electrical engineering and computer science, VSB - Technical university of Ostrava, Czech Republic, from Electrical power engineering branch, in 2005, and received the Ph.D. degree in Electrotechnics, communication and computer engineering, in 2011. Since 2005 he has been with the Department of electrical power engineering. Since 2010 he is a Junior researcher in Centre of energy units for utilization of non-traditional energy sources. He is involved in research of Hydrogen technologies for stationary and mobile application.