INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 15336e15342

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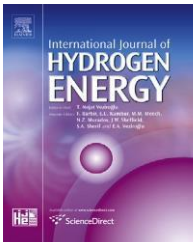

Modeling and simulation of a hybrid photovoltaic (PV) module-electrolyzer-PEM fuel cell system for micro-cogeneration applications

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ARTICLE INFO

Article history:
Received 1 March 2015
Received in revised form
18 June 2015
Accepted 24 June 2015
Available online 15 July 2015

Keywords:
PEMFC
Hybrid energy system
Micro-cogeneration
Electrolyzer

ABSTRACT

The rising cost of energy and power, depreciation of natural resources like fossil fuels and the global warming issues have all led the need for developing advanced clean energy systems. Hydrogen, which is clean energy carrier, can be produced by using solar electric energy from photovoltaic (PV) modules for the water electrolysis without emitting carbon dioxide. Modeling of PV module-electrolyzer hydrogen system is important for their planning and control strategies in many applications. In this respect, high-efficiency co-generation systems for producing both heat and electricity coupled with clean energy sources such as PVs and fuel cells are gaining more attention, due to their advantages in terms of increasing efficiency and power quality, reducing harmful emissions and flexibility of operation. This study describes the analysis of the PV module-fuel cell hybrid system for house-hold micro co-generation applications. The system consists of PV modules, batteries, proton exchange membrane type water electrolyzer and proton exchange membrane fuel cell (PEMFC). The excess heat of PEMFC was used to supply hot water and/or heating energy of the house. Electrical energy was stored in the batteries. The analysis of the PV-electrolyzer-PEMFC system can be further used for designing co-generation systems for various application optimizing the PV module, electrolyzer and PEMFC sizes.

Introduction

The increasing demand for electrical power and energy for heating and cooling of all kinds of buildings led to application of co-generation systems coupled with thermally activated components preferably clean-renewable energy sources [1] since renewable energy is becoming increasingly important as a promising path for replacement of fossil fuels. Among all renewable energy technologies, solar energy is the most promising options for electricity production with use of photovoltaic (PV) modules [2]. Because of the discontinuous

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http://dx.doi.org/10.1016/j.ijhydene.2015.06.122

energy production, energy storage or a backup power system is needed for photovoltaic systems. Batteries can be used for daily storage but for seasonal storage batteries are not practical because of the low storage capacity. Storing energy in the form of hydrogen is a possible solution for both daily and seasonal storage [3]. Hydrogen, which is clean energy carrier, can be produced by using solar electric energy from PV modules for the water electrolysis. Modeling of PV module-electrolyzer hydrogen system is important for their planning and control strategies in many applications such as residential heating and electricity production [4].

Fuel cell-based stationary power generation offers a great market opportunity, because the fuel cell technology is capable of achieving higher efficiencies, with lower emissions as compared to conventional power systems. Residential fuel cell systems can be grid-interconnected to allow power flow from/to the grid as needed [5] Among all fuel cells, proton exchange membrane (PEM) type gain the highest interest because of their high power densities, modular structures and negligible emission rates with respect to the other fuels [6] besides these, PEM types are efficiently coupled to co-generation systems due to their small size, high power production capabilities, and high efficiencies. Using PEM type fuel cells (PEMFC) usually with micro co-generation systems, besides the prime output of the system, which is electrical energy, hot water and/or vapor can also be utilized for household applications.

In the present study a design and analysis of a household-integrated power system is done consisting of PV panels, PEM electrolyzer and PEMFC stack. The PV-PEMFC-CHP system is considered for a residential application of a single household (150 m^2 house, 3e4 people living) for production of electricity and hot water demand of the house for different seasons. Electrical energy is generated in an array of roof mounted solar PV modules and the energy back up is provided through a combination of PEM electrolyzer and PEMFC system. Sunlight is used as the energy input to the system, which is converted to electricity by the PV panels. The electricity produced by the PV panels and PEMFC stack is direct current and needs to be converted to the alternative current by DC/AC converters before supplying to the user. When the generated solar energy is greater than need of the user and also if the hydrogen tank is not full, the extra energy is given to the electrolyzer to produce hydrogen, which is stored in the hydrogen tank for the later usage. The hydrogen stored in the tank is used for PEMFC stack to produce electricity. When the PV system cannot provide sufficient power, stored hydrogen and oxygen are furnished to fuel cells which, smoothly and without interruption.

The performance of the integrated system for different representative seasons of a climatic cycle is presented and analyzed. The study shows that, this integrated hybrid power system provides a viable option for powering stand-alone household in a self-sustained manner.

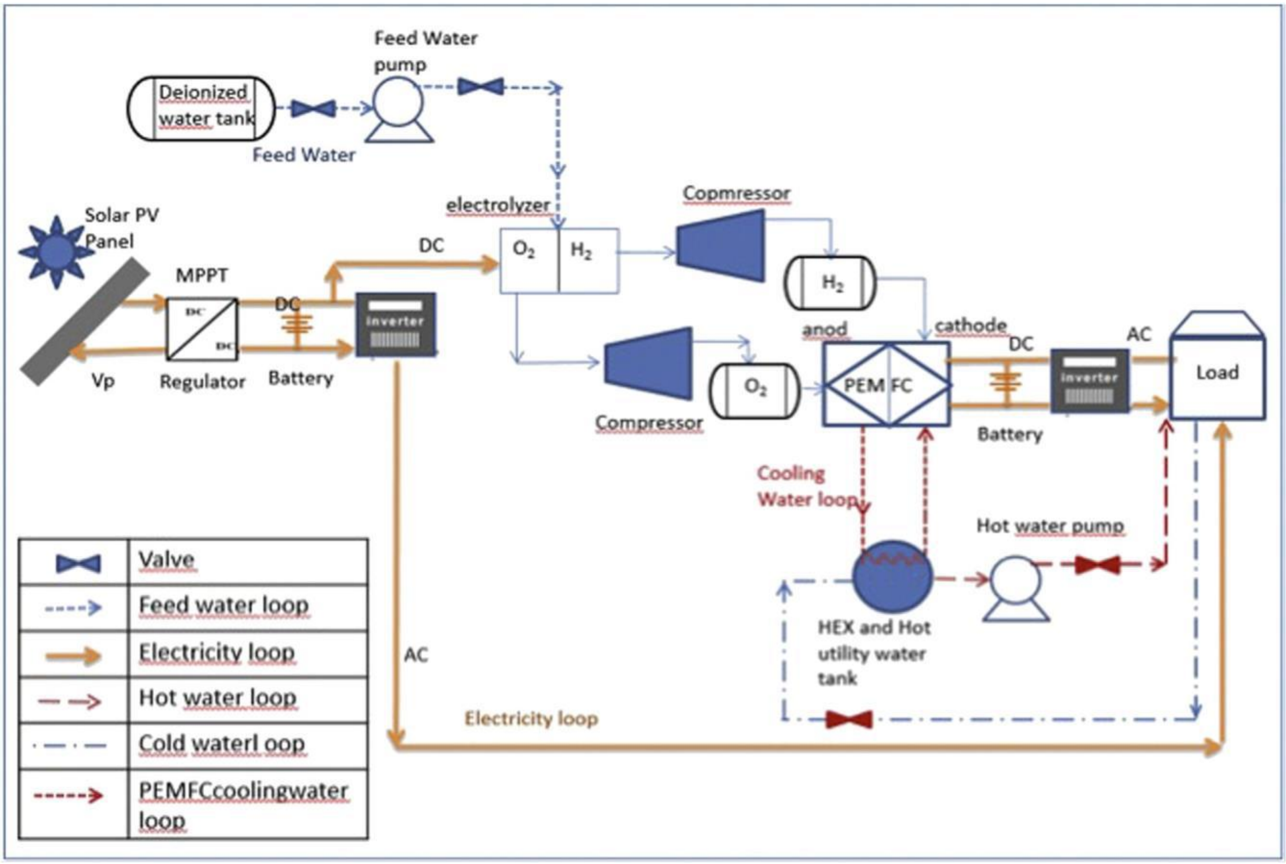

Fig. 1 e Schematics of PV-PEMFC hybrid co-generation system.

Table 2 e Monthly total and average radiation time and radiation per m² for Ankara, Turkey for each month [7]

Months	Monthly total radiation time (h)	Avg radiation time/day (h/day)	Total global radiation (kWh/m²)	Avg global radiation/day (Wh/m²)
January	77.3	2.49	48	1550
February	113.4	3.91	72.8	2510
March	161.3	5.2	121.2	3910
April	200.8	6.69	160.8	5360
May	187.7	6.05	173.8	5610
June	283.7	9.46	232.2	7740
July	281.3	9.07	215.9	6960
August	294.6	9.5	206.5	6660
September	295.9	9.86	175.9	5860
October	169.9	5.48	110.3	3560
November	86.5	2.88	59.1	1970
December	59.7	1.93	43.3	1400

assumed to be 88%. The mass flow rate of the H_2 and O_2 reactants produced from the PEM electrolyzer can be found by the following equation based on Faraday's Laws of Electrolysis:

$$m ¼ \frac{QM}{nF} h_{elec} \quad (4)$$

where m is the mass of the reactant (kg), Q is the total charge passed through the reactant (C), F is the Faraday constant (s A/mol), M is the molecular mass, and n is the valence number. For water PEM electrolyzer, the equation can be rearranged into the following form to find the flow rate required:

$$m ¼ \frac{IDtM}{nF} h_{elec} \quad (5)$$

where m is the mass of the reactant (kg), I is the current passed through the reactant (A), t is the time interval (s), F is the Faraday constant (s A/mol), M is the molecular mass, and n is the valence number.

PEMFC calculations

H_2 flows into the PEMFC at the anode gas inlet. The H_2 concentration N_{H_2}inlet depends on the current density and stoichiometry of H_2. The H_2 concentration at the anode gas inlet of the PEMFC can be defined as follows:

$$N_{H_{2;inlet}} ¼ S_{H_{2;inlet}} \frac{I}{2F} n_{cell} \quad (6)$$

where I is the current density (A/cm^2), F is the Faraday constant, S_{H_2} is the stoichiometry of H_2, and n_{cell} is the number of cells in the PEMFC. The concentration of O_2 at the cathode gas inlet of the PEMFC depends on the current density and stoichiometry of O_2. This concentration of O_2 can be defined as follows: _

production of the PEMFC. The net power production is obtained by subtracting the parasitic loads from the gross power of the fuel-cell stack [11].

Co-generation system calculations

Energy balance in the HEX can be calculated as follows;

$$\dot{m}_{HOT;water} \$ c_{P;HOT} \$ \left(T_{out;hot} - T_{in;hot}\right) ¼ \dot{m}_{cold;water} \$ c_{P;COLD} \$ \left(T_{out;cold} - T_{in;cold}\right) \quad (9)$$

where $\dot{m}_{HOT;water}$ and $\dot{m}_{cold;water}$ are mass flow rates of PEM cooling water and space heating water respectively. $c_{P;HOT}$ and $c_{P;COLD}$ are constant pressure specific heats which are calculated at average water temperatures for hot and cold water sides respectively and $T_{out;hot}$ and $T_{in;hot}$ are hot water inlet and outlet temperatures, $T_{out;cold}$ and $T_{in;cold}$ are cold side water inlet and outlet temperatures respectively. Overall heat transfer coefficient for the HEX is calculated as;

$$\frac{1}{U} z \frac{1}{h_i} þ \frac{1}{h_o} \quad (10)$$

Table 5 e PEMFC design results for different power output.

Power output (W)	H_2 consumption, (slpm)	O_2consumption (slpm)	Heat release (W)
200	3.04	1.52	344
400	6.10	3.04	687
600	9.13	4.57	1030
800	12.17	6.09	1373
1000	15.22	7.61	1717

h

Results

PV results

Electricity production of different PV panel areas for different months are calculated and correlated to electricity consumption for different working hours of the PEMFC. Fig. 2 shows that, minimum electricity production for 17.6 m² panel areas corresponds to 5000 Wh of electricity production during the coldest months and 25,000 Wh during the hottest. It also reveals that, for 1 h operation of the electrolyzer, thus the PEMFC, 17.6 m² is the smallest panel area that can be chosen. Nevertheless, in Fig. 2, also Wh of electricity for 1 h, 2 h, 3 h … of full rated operation of the FC unit are shown added to the graphic. From Fig. 3, it can be observed that, for 2 h of operation for 1 kW PEMFC for all months, a minimum of 33.6 m² panel area is required. In summer months, system can be continuously operated for long hours with very high efficiency, but it is the cold months operation time lack, that constrains the design of the system. In Table 3, estimated prices for panel construction for different areas are given.

For 33.6 m² panel area, corresponding production scheme can be seen in the Fig. 3. This figure shows that, even for the coldest month, PEMFC can be operated at least for 2 h, and between the months of March and October, the system produces almost double electricity and hot water.

Table 3 e Prices for corresponding panel areas [13].

Area (m²)	Price (TL)
17.6	9350
20.8	11,050
24	12,750
27.2	14,450
28.8	15,300
30.4	16,150
33.6	17,850

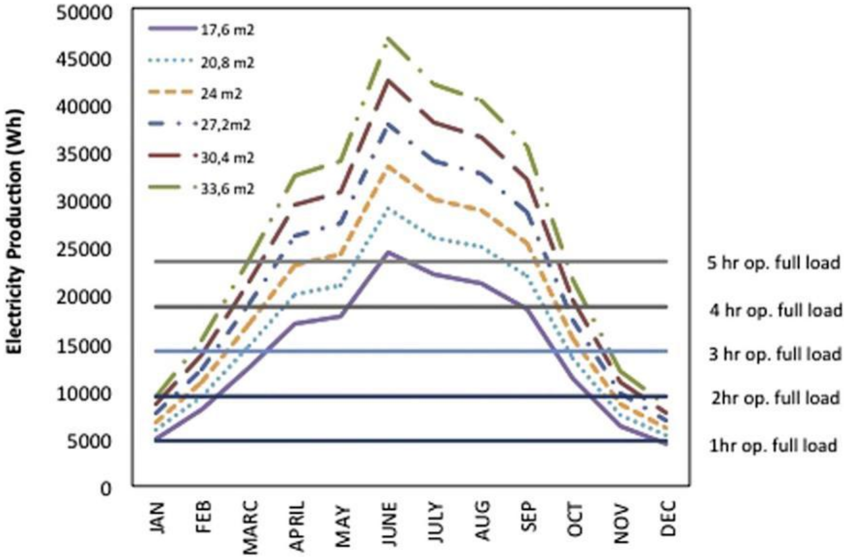

Fig. 2 e Electricity production of the different PV panel area for different months.

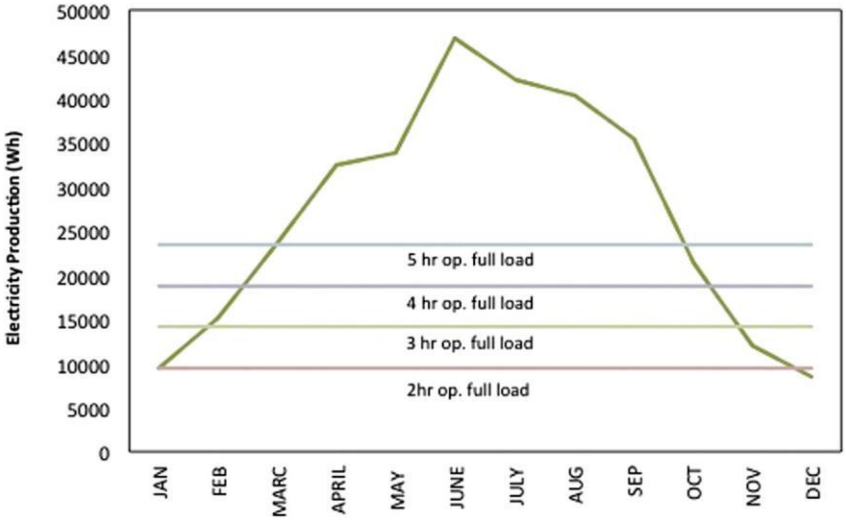

Fig. 3 e Electricity production for 33.6 m² PV panel area for different months.

Table 4 – Electrolyzer system results for different power productions schemes of PEMFC.

PEMFC net power output (W)	Electrolyzer H_2 production (L/min)	Electrolyzer O_2 production (L/min)	Electrolyzer H_2O consumption (L/min)	Electrolyzer power consumption (W)
200	3.04	1.50	0.0027	938
400	6.09	3.04	0.0050	1875
600	9.13	4.56	0.0080	2813
800	12.17	6.09	0.0110	3750
1000	15.21	7.61	0.0134	4688

Electrolyzer results

Electrolyzer system results for different power productions schemes of PEMFC are in Table 4. As seen from Table 4 as expected, H_2 and O_2 production rates are increase with increasing electrolyzer water consumption. The energy requirement of the electrolyzer increases with increasing H_2 and O_2 production.

PEMFC results

PEMFC system results for different power productions values of PEMFC can be seen in Table 5. As seen from Table 5 heat release rate of PEMFC increases with increasing net power. It is also seen that with increase in power output of PEMFC stack, H_2 and O_2 consumptions are increase.

Co-generation system results

Co-generation system results for different power productions values of PEMFC can be found in Table 6. The mass flow rate of heating water can be seen for different heat release rates. It is seen from Table 6 that mass flow rate of the heating water increases with increase in heat release from the PEMFC stack.

Table 6 – Co-generation system results for different power productions values of PEMFC.

Net cell power (W)	Heat release (W)	Mass flow rate of hot water (m^3/min)	Mass flow rate of cold water (m^3/min)	1st pump power (W)	2nd pump power (W)	Compressor power for H_2 (W)	Compressor power for O_2 (W)
200	344	0.0002	0.0001	1.6	1.8	2.9	0.4
400	687	0.0003	0.0002	3.2	3.6	5.8	0.9
600	1030	0.0005	0.0004	4.7	5.4	8.7	1.3
800	1373	0.0007	0.0005	6.3	7.2	11.6	1.7
1000	1717	0.0008	0.0006	7.9	9.0	14.5	2.2

Conclusion

In this study, we have investigated the analysis of the grid integrated hybrid power system consisting of solar photovoltaic panels, electrolyzer and PEMFC stacks. The predicted performance of the integrated system is presented for different climatic conditions, for a given location (Ankara) in the Turkey. The study shows that this hybrid power system provides a viable option for powering stand-alone house in a self-sustained manner. Electric power is generated in an array of PV modules and the power back up arrangement is based on a combination of electrolyzer and PEMFC systems. Excess energy after meeting the requirements of the house during peak sunshine hours, is supplied to an electrolyzer bank to generate hydrogen gas, which is consumed by the PEMFC stack to support the power requirement during the energy deficit hours.

According to the system analysis, between the months of October–March (winter months) developed hybrid system need to take electricity from the grid owing to the low PV performances. On the other hand, between the months of March to October when using the panel area greater than 33.6 m^2, proposed hybrid system can provide its own energy and sell excess electrical energy to the grid.

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