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Photovoltaic Array Sizing for PV-Electrolyzer

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***Abstract*—**Hydrogen that used as fuel in fuel cell vehicles can be produced from renewable sources such as wind, solar, and hydro technologies. PV-electrolyzer is one of the promising methods to produce hydrogen with zero pollution emission. Hydrogen production from a PV-electrolyzer system depends on the efficiency of the electrolyzer and photovoltaic array, and sun irradiance at that site. In this study, the amount of hydrogen is obtained using mathematical equations for difference driving distance and sun peak hours. The results show that the minimum of 99 PV modules are used to generate 1.75 kgH_2 per day for two vehicles.

***Keywords*—**About four key words or phrases in alphabetical order, separated by commas.

I. Introduction

ENERGY production from renewable energy sources such as wind, solar, hydrogen is a sustainable way to generate clean energy from nature without exhaust gases released into our environment. Electrolyzer use direct current to separates hydrogen (H_2) and oxygen (O_2) from water without wasted emission out to the environment. Fuel cell is a device that can produce electricity from hydrogen and oxygen and water vapor and heat are the by-product of its processes. At present, fuel cell has been developed to use in transportation sector such as passenger car, bus, truck, and bicycle because it has higher efficiency than internal combustion engine (ICE) vehicle [1]. Hydrogen as main fuel for fuel cell vehicle (FCV) can be produced from several renewable technologies such as wind, solar, and nuclear energy [2-4]. PV is the semiconductor device that converts sunlight into electricity without moving part hence the emitting exhaust gases and noise are zero during their operations. Hydrogen generated from an electrolyzer can be stored in storage, used instantly in stationary power supply, or fed to hydrogen-driven vehicle. Usually, hydrogen can be kept for several months to later use and the amount of energy can be increased by adding more tanks with minimum cost [5-6]. In this study a stand-alone PV-electrolyzer system for a home hydrogen fueling station for two vehicles is determined. This system is a off-grid PV system where electricity from PV is passed to an electrolyzer for producing hydrogen when sun irradiance is available. Several parameters are taking into account for PV sizing for the PV sizing including the fuel cell vehicle(FCV)'s driving distance, electrolyzer and PV array's efficiency, and sun irradiance at the given site.

The mathematical equations to determine the number of PV modules and the results are presented in this study.

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II. Description of Stand-Alone PV-Electrolyzer System

The typical schematic of a directly connected PV-electrolyzer system is shown in Figure 1 [3, 7]. The major components of a PV-electrolyze system consist of a photovoltaic array, an electrolyzer with compressor, H_2 storage, and fuel dispenser for fueling hydrogen vehicles.

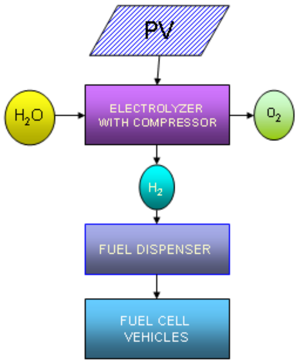

Fig. 1. PV-Electrolyzer System

The detail of each component of the PV-electrolyzer system can be described as the follows;

A. PV Array

The PV modules are connected in series and parallel to form an array that has higher voltage and current. Power output of an array depends mainly on sun irradiance and temperature where the array is located. Maximum power generation of PV is specified in watt peak (Wp) and can be measured at the standard test condition (STC) of 25 °C, sun radiation at 1000 W/m^2, Airmass equals 1.5.

Mathematical equation of a PV array, neglecting shunt resistance and series resistance, can be written as equation (1) using current –voltage relationship known as I-V current characteristic curve[7].

$$I = n_p I_{ph} - n_p I_d \left[e^{qV/AkTn_s} - 1 \right] \qquad (1)$$

Where

- I is the current output of the PV array
- I_{ph} is photocurrent
- I_d is leakage current due to diode effect
- V is the voltage output of the PV array
- n_s is the number of PV module in series connection
- n_p is the number of PV module in parallel connection
- q is the charge of electron ($1.602\text{x}10^{-19}$ Coulomb)
- A is ideality factor (for amorphous =1,crystalline=2)
- k is Boltzmann's constant($1.381\text{x}\ 10^{-23}$)

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T is module's absolute temperature in Kelvin (°K)

There is a point that PV operates at maximum power at constant sun irradiance called maximum power point (MPP). The current and voltage corresponding to MPP are called the maximum current (I_{mp}) and the maximum voltage (V_{mp}). When PV modules are connected in parallel, the maximum current and voltage of the array can be presented as equation(2)-(3)[8].Power at the maximum power point (P_m)of the PV array can be calculated from equation(4).

$$V_m = n_s \cdot V_{mp} \quad (2)$$

$$I_m = n_p \cdot I_{mp} \quad (3)$$

$$P_m = \eta_{pv} \cdot G \cdot A = I_m V_m \quad (4)$$

Where

G is sun irradiance (W/m^2).

A is area of the PV array (m^2)

η_{pv} is efficiency of an PV array

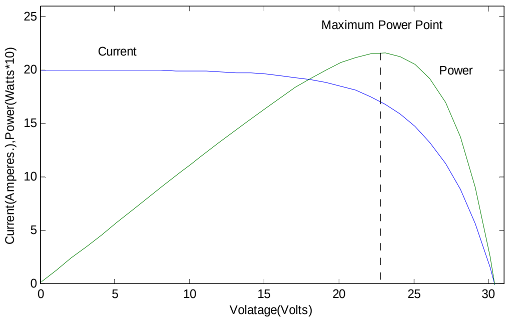

Fig. 2. Current-voltage and power-voltage characteristic curve of a PV array

Energy extracted from solar energy by PV array depends on sun peak hour (SPH) which is the number of hours per day that sun radiance equals 1000 W/m^2. Sun peak hours are different by day, month and season therefore average sun peak hour is used in this study. The energy production per day (E_{pv}) of a PV array can be determined using equations (5).

$$E_{pv} = P_m \cdot SPH \quad (5)$$

B. Electrolyzer

Electrolyzer consists of 2 electrodes and has aqueous electrolyte. Electrolyzer decomposes hydrogen and oxygen from water using electricity [7]. Oxygen occurs on anode and released to the air while the hydrogen on cathode. Hydrogen are the compressed at high pressure then fed to a storage tank that pressure is controlled for more energy density. The overall reaction is presented in equation (6) [8,9].

$$H_2O(l) + E \rightarrow H_2(g)(cathode) + \frac{1}{2}O_2(g)(anode) \quad (6)$$

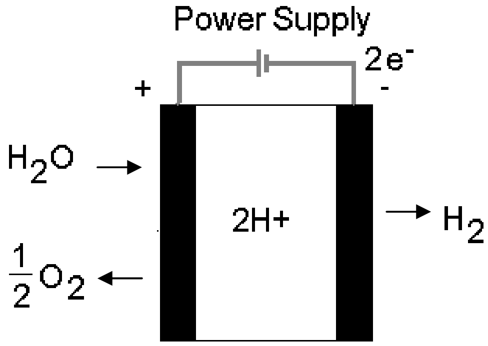

Fig. 3. Electrolyzer Component

The theoretical efficiency of an electrolyzer at normal operation is about 70%[10]. The hydrogen production of 1 kgH_2 requires energy consumption of 39.44 kWh when the normal operating voltage of an electrolyzer cell (V_{ezc}) is 1.76 V. Several electrolyzer cells are connected in series to form an electrolyzer stack. The operating voltage of the electrolyzer stack (V_{ezs}) is presented in equation (7).

$$V_{ezs} = n_{ez} \cdot V_{ezc} \quad (7)$$

Where

V_{ezs} is the operating voltage of an electrolyzer stack.

n_{ez} is number of electrolyzer cells in a stack.

The amount of hydrogen is measured in kilogram (kgH_2) excluding weight of the container at given pressure. The power consumption by an electrolyzer to produce M_{H2} kgH_2 per day for fuel cell vehicles can be determined using equation (8) [11].

$$E_{ezs} = \frac{HHV \times m_{H_2}}{\eta_{ez}} \quad (8)$$

Where

E_{ezs} is the energy consumed by the electrolyzer stack per day (kWh)

η_{ez} is electrical efficiency of the electrolyzer stack

HHV is the higher heating value of hydrogen or the energy contained in the hydrogen 1 kg. (142 MJ/kgH_2 or 39.44 kWh/kgH_2)

For directly connected PV array to the electrolyzer stack, the voltage of electrozer and the PV array are equal and can be written as equation (9).

$$V_m = V_{ezs} \quad (9)$$

PV array supplies power to the electrolyzer stack to generate hydrogen therefore energy transfer between these devices must match and can be presented as equation (10).

$$E_{pv} = E_{ezs} \quad (10)$$

From equations (5), (8) and (10), power of the PV array can be calculated using equation (11).

$$P_m = \frac{HHV \times m_{H_2}}{\eta_{ez} \times SPH} \tag{11}$$

The number of PV modules in series string (n_s) and the parallel string (n_p) can be calculated from equations (12) and(13).

$$n_p = \frac{P_m}{P_1} \tag{12}$$

$$n_s = \frac{V_{ezs}}{V_{mp}} \tag{13}$$

Where

P_1 is rated power of a PV module

C. Fuel Cell Vehicle (FCV)

At present, Only hybrid electric vehicle (HEV) is available in the market. A few hydrogen-driven vehicles are under development because of the high cost of fuel car and lacking of fuel infrastructure [4]. Nevertheless this technology is gaining more attention because it is one of the promising technology for the future for zero emission [12]. Typical hydrogen-driven vehicle keeps hydrogen onboard in hydrogen tanks. Driving distance of each vehicle depends on the amount of hydrogen onboard [2].

The rate of hydrogen usage (C in mile/ kgH_2) for a vehicle must be known by data collection or experimental test. Distance of daily usage normally is in miles per day (D). The overall hydrogen usage per day for every vehicles can be obtained by adding the amount of hydrogen needed by each vehicle. The amount of required hydrogen in KgH_2 for n vehicles per day (m_{H2}) can be determined using equation (14) for the same type of vehicle and driving distance [6].

$$m_{H_2} = \frac{n \times D}{C} \tag{14}$$

For difference types of vehicles and driving distances, the amount of hydrogen can be calculated using equation (15).

$$m_{H_2} = \sum_{i=1}^{n} \frac{D_i}{C_i} \tag{15}$$

In this study the rate of hydrogen usage is 57 mile per 1 kgH_2 [6]. Distance of daily usage for a vehicle is assumed to be the same for two vehicles.

III. Methodology

Photovoltaic array sizing can be done by following 4 steps using equations mentioned in section II,

Step1: Determine the amount of hydrogen required by the vehicles.

Step2: Determine the energy needed by the electrolyzer stack.

Step3: Determine the required PV array .

Step4: Determine the number of PV modules.

IV. Results

Parameters used in this study are shown in Table I. The daily driving distance of vehicles, sun peak hour are varied. The PV system is assumed to obtain energy from the sun during the day and refueling to FCV at the end of day approximately at 17.00 p.m.

In this study the operating voltage of the PV module and the electrolyzer are assumed to match therefore PV modules are connected in parallel only. The amount of hydrogen needed by two FCVs for 50 miles per day is 1.75 kgH_2 results in the maximum number of 120 Wp PV modules of 275 modules at sun peak hours = 3 for energy of 33 kWh while the minimum number is 99 modules at sun peak hours = 5 for energy of 11.9kWh. The number of PV modules is decreased when the sun peak hour and PV module is decreased. Sun peak hour is the essential parameter that must be known at a given site for accurate determination.

TABLE I
Parameter for the Calculation

Description	Unit	Number
Number of vehicles per day	Vehicles	2
Rate of hydrogen usage	Miles/kgH_2	57
Daily driving distance in urban area	Miles	30, 40, 50
Sun Peak Hour	Hours	3, 4, 5
Efficiency of electrolyzer	%	70
Peak watt of a PV Module	Wp	120

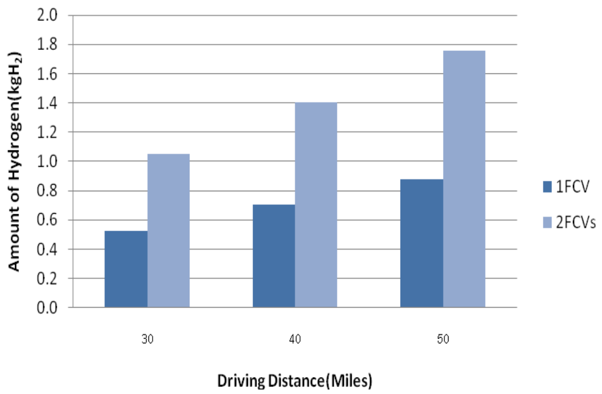

Fig. 4. Amount of Hydrogen for FCVs

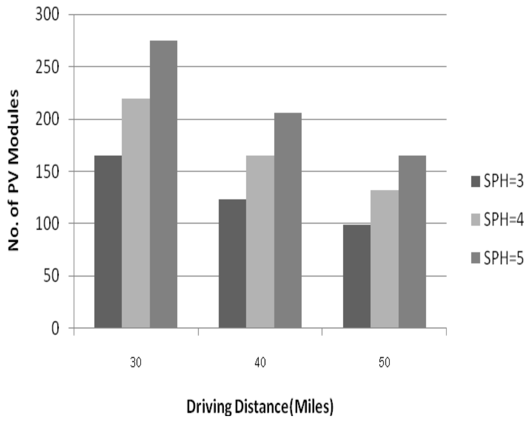

Fig. 5. Number of PV modules

V. Conclusion

PV array sizing for a hydrogen production depends on several parameters; FCV's driving distance, number of FCVs, rate of hydrogen usage, efficiency of electrolyzer and PV array, sun peak hour, peak watt of PV module, and refueling time. In the study the mathematic equations are presented to determined the number of PV modules. The number of PV modules ranges from 99 to 275 modules to produce hydrogen of 1.75 kgH_2 for different sun peak hours. In a stand-alone PV system as the only energy source the large number of PV modules results in the huge investment due to high cost of PV modules. Another option to produce hydrogen from various renewable energy sources is more attractive such as the combination of PV and Wind energy conversion power systems. Users should also take this option with power management into considering before installation the power system to gain more effective energy utilization of renewable energy sources from nature.

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