SIZING AND ECONOMIC ANALYSIS OF HYBRID PV/PEMFC SYSTEMS FOR REMOTE AREAS RESIDENTIAL UTILIZATION

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***Abstract*—** One of the obstacles of using the fuel cells in remote areas is the absence of hydrogen infrastructure to supply the required fuel to the unit. However, this can be solved by producing hydrogen on site from water electrolysis. In this paper, the sizing of a stand alone hybrid PV/PEMFC system to supply electric power for remote residential areas is discussed. The PV system is used to supply the required electric power to a water electrolyzer. The cost of energy (COE) of the hybrid PV/PEMFC system is compared with previous works by the authors for the same residential system when supplied by two individual power sources as two alternatives. The first one is a stand-alone photo voltaic system (SAPV), while the other one is a stand alone PEMFC system. The analysis results will help to define the most economic alternative to supply electricity for remote areas.

Index Terms— PV, PEMFC, Hybrid PV/PEMFC.

List of symbols

Symbol	Description	Unit/value
A	Autonomy days	Days
Ah_B	Battery Capacity	Ah
C_{OM}	O&M cost	$
C_B	The capital cost of the battery	$
C_{IC}	The initial system capital cost	$
C_{LC}	The life cycle cost of the system	$
COE	Cost of energy	$/Wh
d	Interest rate	%
D_e	Electrical power degradation of the FC	%
DOD	Depth of discharge	%
E_e	FC output energy	Wh
E_L	Average residential electrical load	Wh/day
E_Z	Energy consumption of electrolyzer	Wh/l
E_{ZT}	Daily energy consumption of electrolyzer	Wh/day
F	Faraday constant	26.801 Ah/mol
G_S	The relative solar irradiation	%
h_{fc}	FC running hours	h
H_{sun}	Average sunshine hours per day	h/day
H_z	Daily hydrogen production from electrolyzer	l
m_{H2}	FC consumed hydrogen flow rate per unit power of the load	l/min.kw
N_B	Number of batteries	
N_L	Hydrogen volume	L/mol
P_1	The pressure of the hydrogen under standard conditions	Atm
P_2	The pressure of the stored hydrogen	Atm
PC_{BR}	Present value of battery bank replacement cost	$
PC_{CR}	Present value of charger replacement cost	$
PC_{FCR}	Present value of PEMFC replacement cost	$
PC_{IR}	Present value of the inverter replacement cost	$
PC_{KR}	Present value of hydrogen tank replacement cost	$
PC_{TR}	The total replacement cost	$
PC_{ZR}	Present value of water electrolyzer replacement cost	$
P_e	The rated electrical power of the FC	W
P_m	The maximum load power	W
PSV_{Hyb}		$
S_h	Average sunshine hours	hr
SV_B	Salvage value of the battery	$
T_1, T_2	The temperature of hydrogen at P_1 and P_2 respectively	K
V_B	Single battery voltage	V
V_{BB}	Battery bank designed voltage	V
V_{ZC}	Electrolyzer cell voltage	V
V_1	The volume of hydrogen under standard condition	Liters
V_2	Hydrogen tank volume	Liters
y	The life time of each component	Years
Y_{sun}	Total sunshine hours per year	hr
Z_{BB}	Battery bank size	Ah/day
Z_{Chr}	Charge controller size	A
Z_e	The electrolyzer size	l/min
Z_{Inv}	The inverter size	W
Z_{PV}	The PV size	W
η_{Chr}	Charger efficiency	%
$\eta_{DC/AC}$	The efficiency of DC/AC inverter	%
μ_{FC}	Margin coefficient for FC sizing	1.1
μ_V	Margin coefficient for hydrogen tank sizing	1.1
μ_z	Margin coefficient for electrolyzer decomposition voltage	1.5-2.1

I. INTRODUCTION

Photovoltaic (PV) system is considered as one of the most important energy schemes as it is completely safe, clean, and renewable energy source. It has a disadvantage of high Cost Of Energy (COE) due to the required deep-cycle batteries for storing the energy. In deep-cycle batteries, it has low specific energy (0.17 MJ/Kg) which limits its usage in some application due to the required weight of installation. Discharging stored energy in batteries below certain level reduces the life span. Hot climate conditions have certain impacts on the maintenance of such batteries. Life cycle of a battery is critical because when calculating the cost of energy over the Photo Voltaic (PV) panel's life cycle of 30 years, the number of replacements of batteries and their cost will have the highest effect on the COE [1]. Batteries are important element in energy industries but their usage can be minimized to a great extent by using hydrogen as a storage medium.

Hydrogen has the advantages of high specific energy (142 MJ/Kg) which is the third highest specific energy after the Uranium and the Thorium. Fuel cell (FC) is one of the most efficient energy conversion devices. It converts hydrogen by chemical reaction to electrical and thermal power. The Combined Heat and Power Fuel Cell (CHPFC) has high efficiency of 80-85% and low COE [2]. However, the main disadvantage of fuel cells is the absence of hydrogen infrastructure to supply hydrogen fuel. A hybrid PV/PEMFC system is introduced in this paper to get the advantages of the two systems, PV and PEMFC systems, and overcome their disadvantages.

A review of hydrogen production methods is introduced in [3]. The most economical sources to produce hydrogen are by gasification of coal and reforming of natural gas. However, these sources are not reliable due to the reduction of reserves and severe environmental pollution. Also, because of neither infrastructure nor cheap transportation of them, they are not suitable for rural areas residential utilization. Producing hydrogen from water electrolysis has advantage of obtaining high purity hydrogen from sustainable source with zero emission in simple process. A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications is introduced in [4]. Hammou Tebibel and Sifeddine Labed introduce the consumed power of the electrolyzer [5]. However, they don't take into consideration neither the internal electrical resistances due to bubbles, anode and cathode resistance nor the proton conductivity. Also, they neglected the energy enhancement to boost the hydrogen production flow rate. The hydrogen tank size is introduced in [6]. However, it was over sized as the authors calculate the tank size for all the amount of hydrogen generated during the year and this research does not pay attention to the daily hydrogen consumption by the FC.

This paper aims to introduce a sizing methodology for a hybrid PV/PEMFC arrangement for rural areas residential utilization and to analyze the economics of the overall system. A comparison between different water electrolyzer technologies is introduced and equations describing the sizing of hybrid PV/PEMFC are illustrated. The effect of both electrolyzer internal electrical resistance and energy required to boost the hydrogen production flow rate on its actual energy consumption is taken into consideration. The hydrogen tank size is optimized by considering the daily PEMFC consumption and the electrolyzer hydrogen production over the year. The COE is analyzed and compared to that of the standalone PV and PEMFC systems.

II. WATER ELECTROLYZER TECHNOLOGIES

Electrolysis of water is accomplished by using water electrolyzer. The electrolyzer simply consists of an anode and a cathode immersed in water and separated by membrane as shown in Fig. 1. The electrolyzer uses electric current to split water (H_2O) into oxygen (O_2) at the anode and hydrogen (H_2) at the cathode as described by the following equation:

$$H_2O + \underbrace{237.2\,\text{kJ/mol}}_{\text{Electricity}} + \underbrace{48.6\,\text{kJ/mol}}_{\text{Heat}} \rightarrow H_2 + \frac{1}{2}O_2 \tag{1}$$

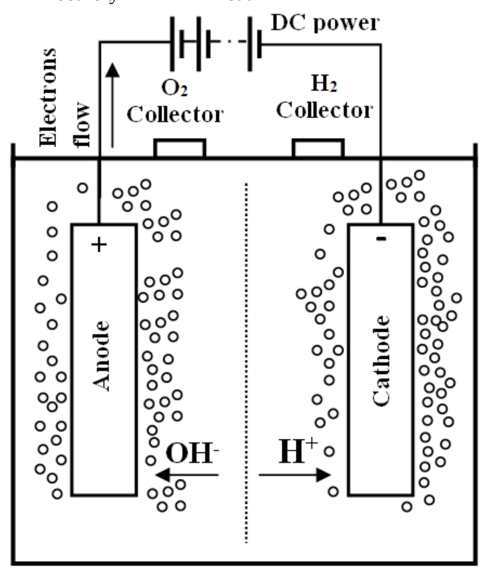

Fig. 1. Basic scheme of water electrolysis system

Currently, there are three technologies to produce hydrogen from water electrolysis. These three technologies are alkaline electrolysis, PEM electrolysis and high temperature electrolysis [7]. The high temperature water electrolysis is called solid oxide electrolysis cell (SOEC). It produces hydrogen from water electrolysis at high temperature (600-1000 °C) to reduce the electrical energy required to split the water. Theoretically, SOEC saves energy up to 23% compared to that at 25 °C, and it has higher energy efficiency than alkaline or PEM water electrolysis for hydrogen production. However, the high temperature constructing materials of SOEC are costly. The high temperature emitting from the SOEC has to be considered for both the surrounding environment and the consumed hydrogen. Till now, the SOEC is in laboratory stage under development [5, 8, 9].

Alkaline water electrolyzers have the following disadvantages over the PEM water electrolysis: wide low partial load range, limited current density and low operating pressure. The wide low partial load range means that the electrolyzer has low efficiency if the load is below 40% of its rated value. The low efficiency results from the low purity of the generated hydrogen. Table 1 shows a comparison between alkaline and PEM water electrolysis. PEM electrolyzers have economical advantages over alkaline electrolyzers in both low operational costs and low gas crossover rate, which allows the PEM electrolyzers to work under a wide range of power input [10, 11].

TABLE 1
COMPARISON BETWEEN ALKALINE AND PEM WATER ELECTROLYSIS

	Alkaline	**PEM**
Working pressure	Low	High
Cell temp.	60-80 (^{o}C)	50-80 (^{o}C)
Availability	Established technology	New market technology
Cost	Relative low cost	High cost
Rating	In MW range	Below MW range
Partial load range	20-40 (%)	0-10 (%)
Stack life time	<90000 (h)	<20000 (h)
Degradation rate	<3 (μV/h)	<14 (μV/h)
Cell area	>4 (m^2)	<0.03 (m^2)
System energy consumption	4.5-7 (kWh/m^3)	4.5-7.5 (kWh/m^3)
H_2 production rate	<760 (m^3/h)	<10 (m^3/h)

III. Sizing Methodology of the Hybrid System

The sizing methodology and the cost analysis will be applied for a small rural residential house. A typical residential load is analyzed as shown in table 2 to define its average daily consumption. In the table, the average electrical load energy (E_L) for a remote area household is about 5 kWh/day and the maximum load power is about 1.3 kW. There are many possible scenarios of the hybrid PV/PEMFC system. However, this study will concentrate on the one shown in Fig. 2.

TABLE 2
ELECTRICAL LOADS OF A SMALL RURAL RESIDENTIAL HOUSE

Appliance	Number	Power [W]	Total power [W]	Working hours [h/day]	Total Energy [Wh/day]
Ceiling fan	2	60	120	5	600
Lamps	6	40	240	6	1440
Refrigerator	1	175	175	6	1050
TV	1	150	150	3	450
Water pump	1	245	245	3	735
Washing machine	1	370	370	2	740
Total			1300		5015

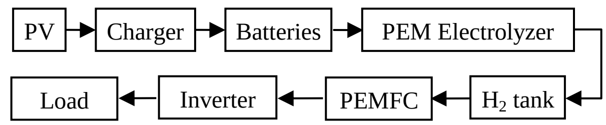

Fig. 2. Configuration of the hybrid PV/PEMFC system.

In this configuration, the stand alone photo voltaic (SAPV) system is used to supply power to the electrolyzer for the hydrogen production which is required as an input fuel to the PEMFC. The residential load is fully supplied from the PEMFC. The sizing equations of both SAPV and PEMFC systems, which are described separately by the same authors in previous work, are as follows [2]:

$$Z_{Inv} = \frac{P_m}{\eta_{DC/AC}} \tag{2}$$

$$P_e = \mu_{FC} \cdot Z_{Inv} \tag{3}$$

The required hydrogen flow rate for the PEMFC is about m_{H2}=14 Lmin^{-1}kW^{-1}. The size of the electrolyzer is determined by its hydrogen production flow rate. As the sunshine hours are different from day to day and from season to season, the total sunshine hours per year will be considered. The electrolyzer size can be calculated by deviding the total amount of hydrogen per year, required from the PEMFC, by the total sunshine hours per year as illustrated in the following equation:

$$Z_e = \frac{m_{H_2} \times E_L \times 365}{Y_{sun}} \tag{4}$$

Generally, the volume of the hydrogen tank V_2 can be determined from the ideal gas law as in (5). However, as the solar irradiation varies during the year, the hydrogen tank has to store the produced hydrogen by the electrolyzer in long daylight-days to use it by PEMFC for short daylight-days. Figure 3 illustrates the sun-shine hours over one year for Wadi Elnatron. The horizontal line that separate region c from regions d and e represent the required time for the electrolyzer to produce the required hydrogen for the PEMFC to supply the residential load for one day. Region c represent the accumulating hours for long daylight-days and regions d and e represent the accumulating hours for short daylight-days. V_1 in (5) represents the daily consumed hydrogen volume by PEMFC plus the excess accumulated volume produced by the electrolyzer in long daylight-days as illustrated in (6).

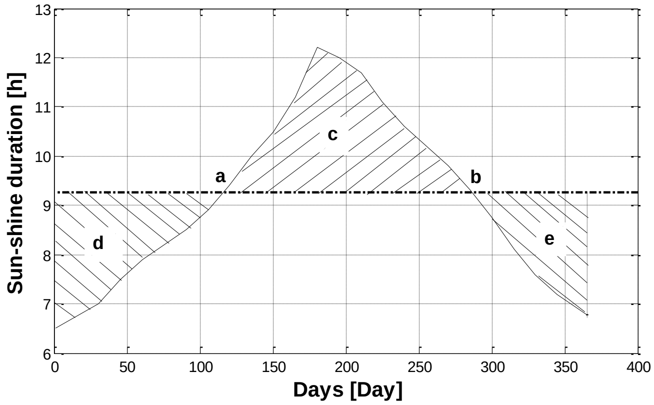

Fig. 3. Sun-shine duration over one year for Wadi Elnatron.

$$V_2 = \frac{\mu_V \cdot V_1 \cdot T_2 \cdot P_1}{T_1 \cdot P_2} \tag{5}$$

$$V_1 = 60\left[m_{H_2}.E_L + Z_e \int_a^b C_{Region} \right] \tag{6}$$

Theoretically, the thermodynamic decomposition voltage of water is 1.23V. However, in industrial water electrolyzer, the chemical reaction for splitting the water into oxygen and hydrogen occurs at electrolyzer cell voltage of 1.8 V up to 2.6 V. This over potential is used for increasing the hydrogen production rate and overcoming the ohmic voltage drop due to the resistance of electrolyte, membrane, bubbles and electrical circuit. The energy consumption of water electrolyzer can be calculated as illustrated in [8]. However, this study is based on the theoretical thermodynamic decomposition voltage of water rather than the industrial electrolyzer cell voltage. The energy consumption of water electrolyzer will be modified to be calculated as follows:

$$E_Z = \frac{2 \cdot \mu_Z \cdot F \cdot V_{ZC}}{N_L} \tag{7}$$

Regardling the previous equation, the actual energy consumption of water electrolyzer ranges between 4.31-6.22 kWh/m^3. However, the theoretical value is 2.94 kWh/m^3. The daily total consumed energy of water electrolyzer will equal the value given by equation (7) times the total volume of hydrogen production per day as follows:

$$E_{ZT} = E_Z \cdot H_Z \tag{8}$$

The size of the solar system, including solar panel size, charge controller size and batteries bank size- will be as follows [1]:

$$Z_{PV} = \frac{E_{ZT}}{G_S \cdot H_{sun}} \tag{9}$$

$$Z_{BB} = \frac{A}{DOD} \times \frac{E_{ZT}}{V_B} \tag{10}$$

$$N_B = \frac{Z_{BB}}{Ah_B} \tag{11}$$

$$Z_{Chr} = \frac{1}{\eta_{Chr}} \times \frac{Z_{PV}}{V_{BB}} \tag{12}$$

IV. LIFE CYCLE COST METHODOLOGY OF THE HYBRID SYSTEM

The life cycle cost of the hybrid PV/PEMFC can be calculated by the following equation:

$$C_{LC} = C_{IC} + C_{OM} + PC_{TR} - PSV_{Hyb} \tag{13}$$

The initial capital cost (C_{IC}) is the sum of purchase cost of each component in the system for the first time. The O&M cost (C_{OM}) will be calculated for three components: PV system, PEMFC and water electrolyzer. Regarding PV system, it represents the cost of adjusting the PV modules tilt, cleaning to remove dirt and dust, and batteries maintenance such as adding water and cable checking. Regarding the PEMFC and water electrolyzer, the O&M cost will be for both the spare parts and checking the air, hydrogen, and water systems. The present value of the total replacement cost (PC_{TR}) will be calculated as follows:

$$PC_{TR} = PC_{BR} + PC_{CR} + PC_{IR} + PC_{KR} + PC_{FCR} + PC_{ZR} \tag{14}$$

The present value of the total replacement battery bank cost along the PV life time will be calculated as follows:

$$PC_{BR} = \sum_{y=5}^{Y} \frac{C_B}{(1+d)^y}, y = 5,10,\ldots,25 \tag{15}$$

Table 3 illustrates the life cycle time of each system component. Since the PV panels have the largest life cycle in the system, the overall system life cycle will be 30 years and the other components will be multiply replaced according to this period [12,13].

TABLE 3
THE LIFE CYCLE TIME OF HYBRID PV/PEMFC COMPONENTS

Component	Life cycle [Years]
PV panels	30
Charge controller	10
Deep cycle batteries	5
PEM electrolyzer	10
H_2 tank	15
PEMFC	6
Inverter	10

Equation (15) will be applied for each term of equation (14) and the steps of changing "y" will vary according to each component life cycle.

The salvage value of the battery bank at the end of its life cycle can be calculated from the following equation [1]:

$$SV_B = K_h(1 - K_r - K_u)C_{BB} \tag{16}$$

The cost of energy (COE) can be calculated by dividing the life cycle cost of the system over the total generated energy during the system life cycle as follows:

$$COE = \frac{C_{LC}}{E_e} \tag{17}$$

The total generated energy during the system life cycle concerning the effect of the electrical energy degradation on FC output will be as follows:

$$E_e = \sum P_e h_{fc} \left[1 - \left(\text{floor} \frac{h_{fc}}{10^3} \right) D_e \right] \quad (18)$$

V. RESULTS AND DISCUSIONS

The previous sizing methodology has been implemented for Wadi Elnatroun region, Egypt. The monthly average solar radiation and the sunshine hours, over a period of one year has been obtained from the World Radiation Data Centre (WRDC) as illustrated in Table 4. The global solar radiation over one year is illustrated in figure 4.

To determine the COE and the percentage cost of each component in the system, the calculations are performed according to the previous equations considering the following assumptions [1, 2, 13, 14]:

1) The O&M cost of the PEMFC is 0.035 $/kWh.
2) The electrolyzer O&M cost is 5% of its capital cost.
3) The FC salvage value is 10% of its capital cost.
4) The salvage value will be considered for FC and battery bank only.

Table 5 summaries the size of each component in the system in addition to its cost.

TABLE 4
THE DAILY AVERAGE SOLAR RADIATION AND THE SUNSHINE HOURS OVER A PERIOD OF ONE YEAR AT WADI ELNATROUN

	G[W/m²]	S_h[hr]
January	420	7.5
February	493	8.3
March	579	9.3
April	636	9.7
May	564	11.4
June	577	12.2
July	590	12.2
August	580	11.3
September	535	10.7
October	484	9.1
November	416	8.4
December	427	6.6

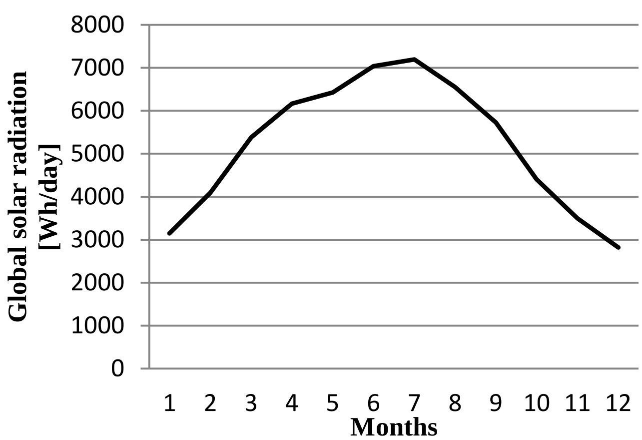

Fig. 4. Daily average solar radiation per month

TABLE 5
THE SIZE AND COST OF EACH SYSTEM COMPONENT

Component	Size	Cost [$]
PV	3666 W	3666
Charge controller	85 A	589
Battery bank	4000 Ah	5900
Electrolyzer	8.6 L/min	65000
H_2 tank	900 L	1320
PEMFC	1800 W	7500
Inverter	1500 W	1290

The pie-chart illustrated in figure 5 shows the percentage cost of each component of the hybrid PV/PEMFC system within 30 years of PV life time. It is clear from the pie-chart that the water electrolyzer represents the major COE. The running cost represent the second major COE, 21%, which include both the battery and the O&M cost.

The COE for the hybrid PV/PEMFC is compared with that obtained in other two papers of the same authors. One for the standalone PV system and the other for standalone PEMFC system [1, 2]. The bar graph of figure 6 shows that the hybrid PV/PEMFC system provides lower COE. However, the system becomes a little bit complicated.

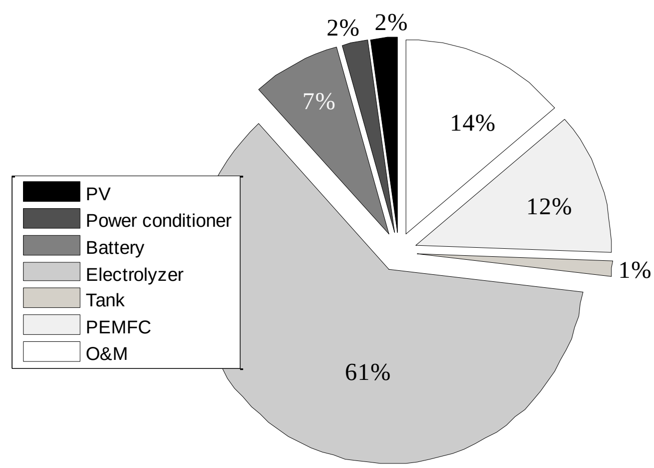

Fig. 5: The percentage cost of each component in the hybrid PV/PEMFC system over 30 years

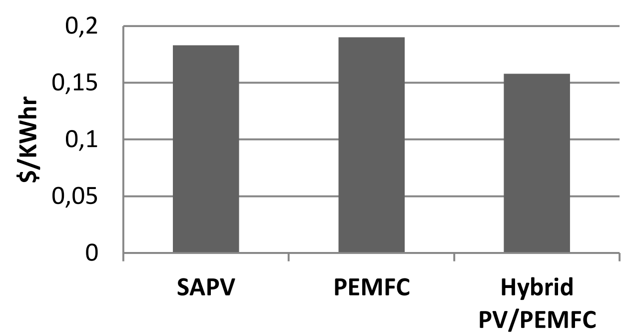

Fig. 6: The COE for three standalone alternative systems

Table 6 illustrates a comparison among SAPV, standalone PEMFC, and hybrid PV/PEMFC systems.

TABLE 6
A COMPARISON AMONG SAPV, PEMFC, AND HYBRID PV/PEMFC.

	SAPV	PEMFC	Hybrid PV/PEMFC
COE [$/Kwhr]	0.183	0.19	0.158
Meed for fossile fuels	×	✓	×
Infrastructure	×	✓	×
Depedence on climate conditions	✓	×	✓
Possibility of explosions	×	✓	✓

VI. CONCLUSIONS

An economic analysis of a hybrid PV/PEMFC system for residential applications is carried out to define the size of each component and the COE over the system life time. The effect of both electrolyzer internal electrical resistance and energy required to boost the hydrogen production flow rate is considered when sizing the energy consumption of the electrolyzer. The optimum size of the hydrogen tank is designed by considering both the PEMFC daily hydrogen consumption and the yearly water electrolyzer hydrogen production. The COE is calculated by dividing the life cycle cost of the system by both electrical and thermal energy produced over its life time.

The analysis show that the hybrid PV/PEMFC has lower COE compared to both standalone PV system and stanalone PEMFC system. The electrolyzer cost plays the major role for defining the COE. More investigation is required to reduce the cost of water electrolyzer or develop new method to produce hydrogen on site with high purity for small scale.

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