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Modeling a hybrid system for electrical generation and wastewater treatment using photovoltaic and fuel cells

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ABSTRACT

The need to shift to eco-friendly fuel and to recycle wastewater is increasing rapidly with the depletion of non-renewable energy resources and scarcity of water. This study highlights importance and need to promote the efficiency of clean processes for wastewater treatment. It also examines sound environmental methods for water generation with a special focus on solutions for remote areas with limited electricity, sewage networks and irrigation water. Such methods employ modern technology for treatment of wastewater for power generation purposes. The study further proposes a power management strategy for solar and fuel cells system for domestic use in Hebron City. The design was developed to meet total load demand without necessarily being connected to the grid. However, double chambered microbial fuel cell (MFC) prototype was used to treat domestic greywater and to generate some electricity. Chemical oxygen demand removal efficiency achieved was 73.6% and 65.4% for dissolved solids removal. The performance of the MFC decreased, when the wastewater concentration was decreased. Thus, MFC can provide clear water, which can be electrolyzed by excess power from PV panels into Hydrogen and Oxygen. Hydrogen will be used to generate the electricity by fuel cell.

Keywords: Fuel cell; Hybrid systems; Microbial fuel cell; PV; Wastewater treatment

1. Introduction

Literature review showed that several researchers have studied the use of microbial fuel cell (MFC) for wastewater treatment and operation of a hybrid system of PV and proton exchange membrane fuel cell (PEMFC) with electrolyzer. in which they provide the relevant information related to the technology and will give the reader an understanding of the design, function, important and potential use. Former research explained the MFC technology providing readers with an understanding of the design and its function as well as its potential use. Further research examined the hybrid system using fuel cells and PV [1–5].

With increased emission of greenhouse gases including carbon dioxide from burning fossil fuels, the planet started to endure global warming, deforestation and depletion of clean water resources. Henceforth, researchers started to consider alternative environment-friendly sources of energy/fuel to replace nuclear and fossil sources. The solutions envisaged also focused on replenishing clean water resources. Additional measures would include sharp cuts in the emission of greenhouse gases. To ensure sustainability of sources of energy and clean water, it is paramount to devise solutions to save these precious resources while meeting the increasing global demand [6,7]. Water scarcity is already a global issue affecting all five continents as one-fifth of the world population under physical shortage while another half a billion people are approaching this situation.

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Moreover, one quarter of the world population do not have access to water because of economic reasons. On the other hand, 18% of the world's population do not enjoy access to electricity. The traditional grid connection is not a practical or economically feasible solution for many rural areas, which makes the off-grid home system a more appealing solution [8–10]. A possible solution for stand-alone power generation is to use a hybrid energy system in parallel with new technologies, such as hydrogen technology for storage energy. Renewable energy sources (solar, wind, hydrogen, etc.) are attracting more attention as alternative sources to traditional fuel. MFC technology represents a new form of renewable energy, which transforms the organic matter into electricity while treating the wastewater. Most people live in villages without connection to utility lines. They represent the largest potential market for stand-alone hybrid systems [6,7,11–14].

The study presents a PV-fuel cells hybrid method that allows for wastewater treatment in addition to electricity generation and proposes it can be a solution for power shortage in some areas.

2. Load profile of electricity consumption

Fig. 1 shows the block diagram of the system. The system utilizes photovoltaic (PV) as the primary power generator, PEMFC as the secondary backup power generator, electrolyzer (to store any excess power) as power storage device and the MCF to treat greywater and generate more power. The system presents a double advantage allowing for continuing energy supply to households and treatment of wastewater in the same time. The theoretical study focuses on the behavior of hybrid system. In addition, the proposed system is being environmentally friendly, decreasing noise and carbon footprint. A cost-benefit analysis reveals the advantages gained by proximity to users creating thus self-sufficient, less costly and stand-alone power systems. The design process starts with an assessment of the loads need to operate the system.

Data was collected from a house in the south of Hebron city, with six inhabitants and a total area of 160 m^2 and Latitude of +31.54 (31°32′24″N) and +35.09 (35°05′24″E) Longitude. Power needed by a load, as well as energy required over time by that load, is important for system sizing. The energy (Wh or kWh) is the product of some nominal power rating of the device multiplied by the hours that is used [Eq. (1)]. Table 1 lists examples of power used by a number of household electrical loads. After knowing the number of hours of use per appliance, we can calculate the energy consumption per appliance and henceforth, the total energy consumption every day of the month. January and July were identified as the two months with peak consumption of electric power throughout the year in Hebron. Table 2 shows the average daily energy consumption for household appliances in January.

$$E = P * T \tag{1}$$

where P: power consumption (kW), E: energy consumption (kWh), T: period of time that the appliance was operated (h).

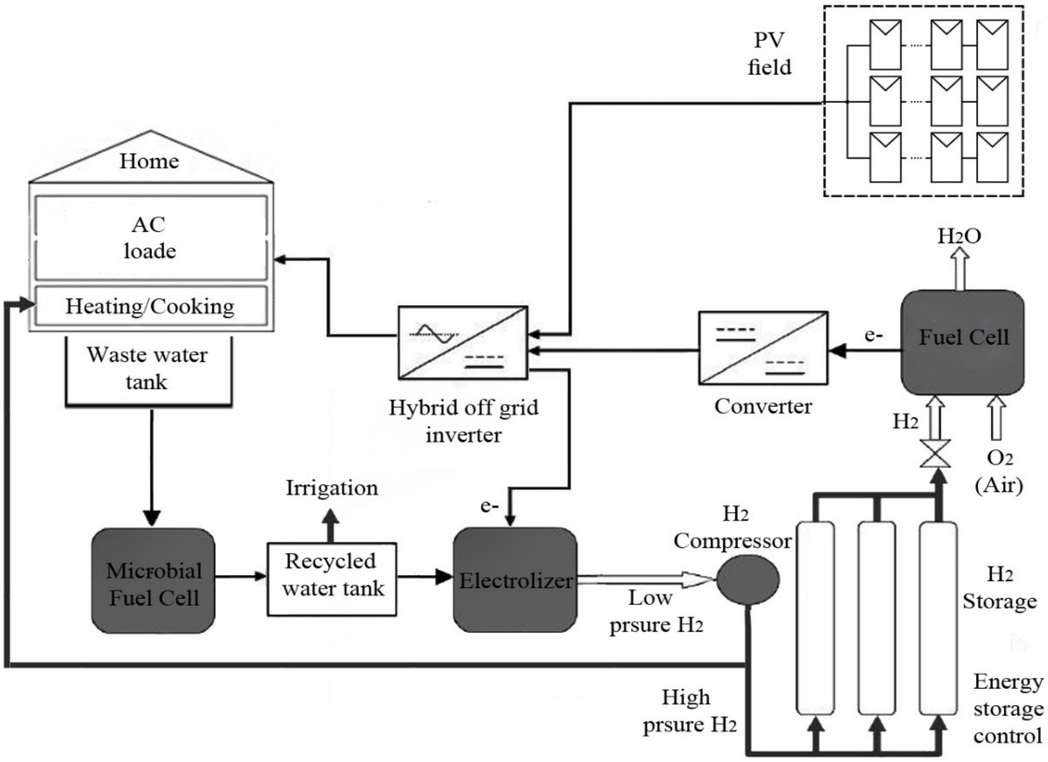

Fig. 1. System block diagram.

Fig. 2 shows a comparison between household loads in winter (January) and summer (July). Findings showed that more energy is consumed in the winter compared to the summer because of several reasons: 1) the operation hours for many appliances are longer in winter. This includes, for instance,use of electricity heaters and water kettles, and longer lighting hours.

As stated earlier, the year was divided into two main seasons, summer and winter. The energy consumption curve was drawn to show daily/monthly consumption. Two peaks were identified on the curve (January–February (P1) and July (P2)). The least consumption appeared in May (L1) and October (L2). The total consumption for 12 months reached 4116 kWh/y.

Table 1
Power requirements of typical loads [15]

Appliance	Power(W)
Kitchen appliances	
Refrigerator: ac EnergyStar, 19 cu. ft	300 W, 1140 Wh/d
Refrigerator: dc Sun Frost, 12 cu. ft	58 W, 560 Wh/d
Microwave oven	750–1100 W
Coffee maker (warming)	600 W
Toaster	800–1400 W
General household	
Furnace fan: 1/4 hp	600 W
Air conditioner: window, 10,000 Btu	1200 W
Heater (portable)	1200–1875 W
Fluorescent lamp	35 W
Clothes iron	1000–1800 W
Electric clock	4 W
Consumer electronics	
TV: >39-in. (active/standby)	142/3.5 W
Satellite receiver (active/standby)	17/16 W
VCR (active/standby)	17/5.9 W
Component stereo (active/standby)	44/3 W
Laptop compute	20 W

3. Load profile of water consumption

Embedded energy in water refers to the amount of energy that is used to collect, convey, treat, and distribute a unit of water to end-users. Water consumption data and load profiles of major household appliances are crucial

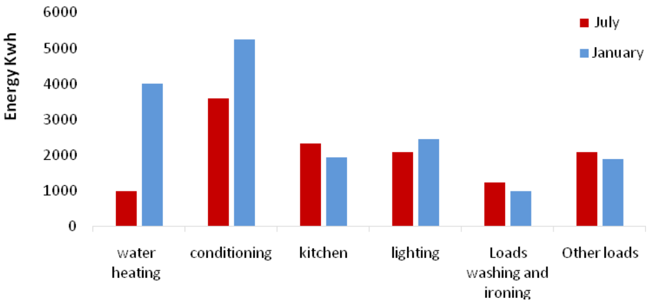

Fig. 2. The comparison of proportion of major household loads between winter and summer.

Table 2
The average daily energy consumption for household appliances in January

#	Appliance	Quantity	Power rating (W)	Operating time (h/d)	Energy Consumption (Wh/d)	Percentage (%)
1	Refrigerator 22 cu.ft	1	300	3.8	1140	6.9
2	Microwave	1	800	1.5	800	4.8
3	Heater	1	750	7	5250	31.8
4	Fluorescent lamp	10	35	7	2450	14.8
5	Iron	1	1000	0.5	500	3.0
6	Hair dryer	1	1000	0.3	300	1.8
7	Washing machine	1	500	1.5	500	3.0
8	Computer active mood	1	44	3	132	0.8
9	Computer Standby mood	1	3	21	63	0.4
10	Satellite receiver active mood	1	17	4	68	0.4
11	Satellite receiver Standby mood	1	16	20	320	1.9
12	TV 39 in active mood	1	142	4	568	3.4
13	TV 39 in Standby mood	1	3.5	20	70	0.4
14	Phone	2	4	2	16	0.1
15	Laptop computer	2	20	5	200	1.2
16	Radio	1	75	2	150	0.9
17	Fan	2	300	0	0	0
18	Water heater	1	1000	4	4000	24.2
	Sum				16972	100

elements for demand response studies. The load profiles of major household appliances in Palestine includes baths, showers, toilets, washing machines, dish washers and faucet. Table 3 shows the aggregated hourly water demand for a single family and low-income single-family indoor (LISF). Fig. 4 shows the disaggregated hourly water demand activities of LISF Indoor.

4. PV-PEM fuel cell system sizing and design

4.1. Sizing PV generator

Palestine is located in a region with considerably high solar radiation. The daily average of solar radiation in Palestine amount to 5.401 kWh/m^2/d. The important parameters for system sizing are the average daily solar radiation energy and the load consumption. The total consumption of 12 months is 4116 kWh/y (Fig. 5). Moreover, the average number of hours at peak sun daily for Hebron city is 5.4 h/d. The modules PV are Polycrystalline Silicon with an efficiency of about 15.9%. The PV system generates electricity to the house via an off grid hybrid solar inverter with 93% efficiency.

To determine the size of the PV modules, the day is divided into two periods: first the consumption of PV power (43.6% of daily consumption as shown in Fig. 5); other than PV generated power (56.4% of daily consumption as shown in Fig. 6), which takes into consideration the efficiency of PEM fuel cell and electrolyzer alike.

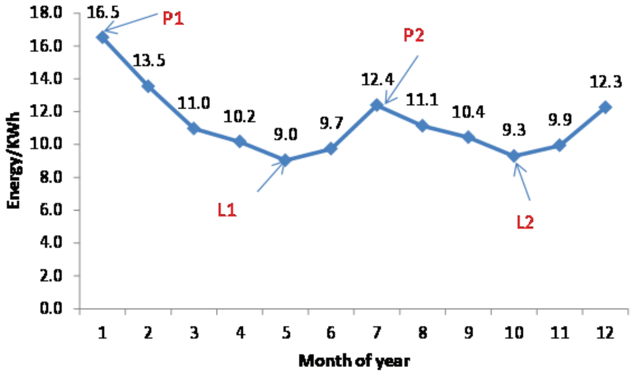

Fig. 3. The curve day/month during the year

$$\text{Power loss at } \%\left(\frac{\Delta P}{°C}\right) = 0.48\% \text{ per degree above 25°C},$$

NOCT = 50 (datasheet values)

$$T_{CELL} = T_{amp} + \frac{NOCT - 20}{0.8} * 1SUN \tag{2}$$

$$T_{CELL} = 20° + \frac{50° - 20°}{0.8} * 1SUN = 57.5°C$$

$$P_{dc\_STC} = 1\ KW \times (1 - \%(\Delta P/1))(T_{cell} - 25°) = 0.844\ kw \tag{3}$$

$$\eta_{temp} = \frac{P_{dc\_STC}}{1kw} = \frac{0.844kw}{1kw} = 0.844 \tag{4}$$

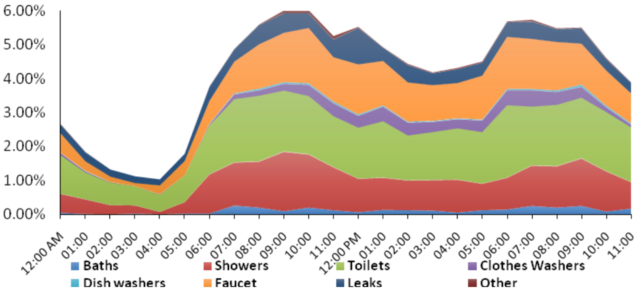

Fig. 4. Disaggregated hourly water demand activities – LI.SF indoor.

Table 3
Aggregated hourly water demand – single-family and low-income single-family indoor [16]

Hour	SF % of total daily indoor water use	Li.sf % of total daily indoor water use	Hour	SF % of total daily indoor water use	Li.sf % of total daily indoor water use
12:00 AM	1.88%	2.06%	1:00	4.34%	4.39%
1:00	1.37%	1.08%	Total before peak	54%	51%
2:00	1.24%	0.84%	2:00	4.00%	4.16%
3:00	1.11%	0.86%	3:00	4.31%	4.23%
4:00	1.37%	1.15%	4:00	4.62%	4.73%
5:00	2.58%	1.35%	Total during peak	13%	13%
6:00	5.01%	4.38%	5:00	4.87%	5.55%
7:00	6.64%	5.54%	6:00	5.36%	5.58%
8:00	6.43%	6.42%	7:00	5.49%	5.34%
9:00	6.38%	6.37%	8:00	5.19%	5.90%
10:00	5.76%	5.86%	9:00	4.75%	5.47%
11:00	5.38%	5.65%	10:00	4.07%	4.71%
12:00 PM	4.86%	5.02%	11:00	2.97%	3.35%
Total after peak				33%	36%

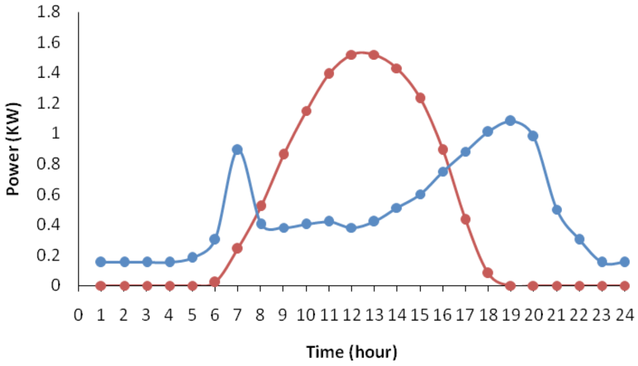

Fig. 5. The load demand and the output power of the PV generator.

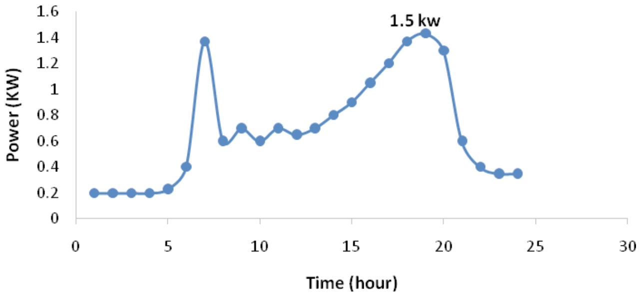

Fig. 6. Behavior of maximum consumption load pattern per day in the year.

The conversion efficiency in the section using PV generated power is:

$$\eta_{Conversion1} = \eta_{dirty\_collector} \times \eta_{Mismatching} \times \eta_{inverter} \times \eta_{Temp}$$
$$\eta_{Conversion1} = 0.96 \times 0.97 \times 0.93 \times 0.844 = 0.7309 \tag{5}$$

The conversion efficiency in the absence of power generated by the PV is:

$$\eta_{Conversion2} = \eta_{dirty\_collector} \times \eta_{Mismatching} \times \eta_{inverter} \times \eta_{Temp} \times \eta_{FC} \times \eta_{ele}$$
$$\eta_{Conversion2} = 0.96 \times 0.97 \times 0.93 \times 0.844 \times 0.56 \times 0.85 = 0.3479 \tag{6}$$

$$Energy\ \left(KWh / year\right)\ = P_{ac}\ \left(KW\right)\ \times\ \mathrm{CF} \times\ 8760\ h / yr \tag{7}$$

$$Capacity\ factor\left(CF\right) = \frac{\left(\dfrac{h}{day} of\,"peak\,sun"\right)}{24h / d} = \frac{5.401}{24} = 0.2251 \tag{8}$$

$$P_{ac} = \frac{energy\left(KWh / yr\right)}{\mathrm{CF} \times 8760(h / yr)} = \frac{4116}{0.2251 \times 8760} = 2.0874\,KW_{AC} \tag{9}$$

$$\begin{aligned} P_{dc\,1} &= \frac{P_{ac}}{\cdot_{\text{conversion}1}} \times 43.6\% = \frac{2.0874kw}{73.09\%} \times 43.6\% = 1.245\,KW_{Peak(DC)} \\ P_{dc\,2} &= \frac{P_{ac}}{\cdot_{\text{conversion}2}} \times 56.4\% = \frac{2.0874kw}{34.79\%} \times 56.4\% = 3.384\,KW_{Peak(DC)} \\ P_{dc\ total} &= P_{dc\,1} + P_{dc\,2} = 1.245 + 3.384 = 4.629KW_{Peak(DC)} \end{aligned} \tag{10}$$

$$Number\ of\ PV\ panels = \frac{P_{DC\,(PV)}}{P_{panel}} = \frac{4.629k}{260} = 17.804 \cong 18\,panels \tag{11}$$

$$\begin{aligned} P_{dc\_STC} &= \frac{1kw}{m^2} at\,1\,sun * Area * \eta_{pv} \\ Area\,of\ PV &= \frac{4.456kw}{\dfrac{1kw}{m^2} * 0.159} = 28.03\,m^2, \eta_{pv} = 15.7\% \end{aligned} \tag{12}$$

4.2. Sizing the PEM fuel cell

The PEM fuel cell supply is required when there is not enough solar radiation and in the night. Its power can be calculated based on the maximum load required.

Since the peak of daily consumption appeared in January with 1500 W (Fig. 6), we chose the rate power for PEF fuel cell – 1500 W with efficiency of 56%, accounting as well for a rise in consumption in the future. There is a need for three 500-W fuel cells to be connected in series with a start-up batter of 13.5 V and a converter to step up voltage for the inverter.

4.3. Sizing an electrolyzer

The rated power of the electrolyzers can be calculated by the Eq. (10):

$$P_{el} = P_{PV} - P_{L,min} = 1832 \quad 370 = 1462\mathrm{W} \tag{13}$$

where P_{el} is rated power of the electrolyzer, P_{PV} is output power of PV modules, $P_{L,min}$ is minimum of the clinic load.

5. Microbial fuel cell design and experiment

The annual energy used for the water infrastructure was 5–6% of all electricity generated and for wastewater treatment. The low initial and operating cost of MFC makes it appealing to people in areas without access to conventional power grids and water networks, but who – nonetheless – need electricity and safe water. This project depends on natural resources (mainly sun and water) to create sustainable and environment-friendly energy for use in areas suffering from water shortage. It is also a proper alternative when energy is not readily or economically available. Wastewater was collected from the six-person house in Hebron over a period of 10 d. The sample included only greywater. The chemical oxygen demand (COD chromate) was around 1270 mg/L. the Fuel cell is an electro-technical device that produces electricity directly from chemical energy. Microbial fuel cells (MFC) diverts chemical substance including bacteria to power the cells. MFC gained worldwide interest a solution to directly generate electricity from organic material like wastewater. It uses bacteria to catalyze the conversion of organic material to electricity. Bacteria generate electrons and protons in anode from oxidized substances and electrons are transferred through an external circuit.

5.1. The experimental study on MFC

A double chambered MFC was fabricated. The reactor was fabricated using non-reactive plastic containers with total volume of 3 L and the working volume of 2.8 L. Six graphite rods from pencils were used as both anode and cathode materials. The arrangement of graphite rods (35 mm in length and 6 mm in diameter) was made in such a way as to provide the maximum surface area for the development of biofilm on anode. The electrodes were connected using copper wire. The anode and the cathode chambers were separated by agar salt bridge, the salt bridge consist of 10% agar in 0.1 morality of NaCl poured into 100 mL plastic pipe to make a gel, allows for hydrogen protons yielded by the bacteria to pass through (see Fig. 7). The length and diameter of the agar salt bridge were 100 mm and 60 mm respectively. The electrodes were placed in the chambers and were later sealed and made airtight and checked for water leakages. The experiment test was conducted by feeding different strengths of grey wastewater (100% strength without any dilution, 75% strengths by diluting with 25% distilled water). The anode chamber was filled with wastewater and the cathode chamber was filled with 1 molar of NaCl solution. The internal wiring of anode and cathode was connected to a multi-meter to complete the circuit. The entire setup was left for one hour for stabilization process. However, the reading in the multi-meter was taken twice every 24 h throughout a month of operation. On the other hand, in the semi-batch condition, the paraffin was added at top layer on the tank to prevent oxygen from entering the tank and so, creating anaerobic circumstances. The samples were analyzed each 24 h every 24 d for both 100% and 75% concentrated greywater.

The wastewater samples were obtained from a house with 6 inhabitants. The tests include COD, TDS and the current was measured to the sample from input tank after the set up in different conditions. Table 4 illustrates greywater original sample characteristics.

Fig. 8 illustrates the COD and TDS during batch and semi batch conditions. It can be seen that both COD and TDS drop significantly with time. Continuous COD removal was observed in MFC during all operation days while the greywater concentration in the batch was 100 %; the semi-batch was initially full strength wastewater used in the anodic chamber, and then it was replaced by 75% concentrations. Experimental data indicated that COD removal efficiency was decreased with the decrease of wastewater concentration from 100% to 75%. The COD removal efficiency using grey wastewater at 100%, 75% wastewater concentrations were 45.29% in batch and 55.37%, 50.12% respectively in semi batch. This relative slow COD removal was possibly due to less availability of biodegradable substrate in 75% than that of full strength wastewater leading to competitive inhibition in microorganisms.

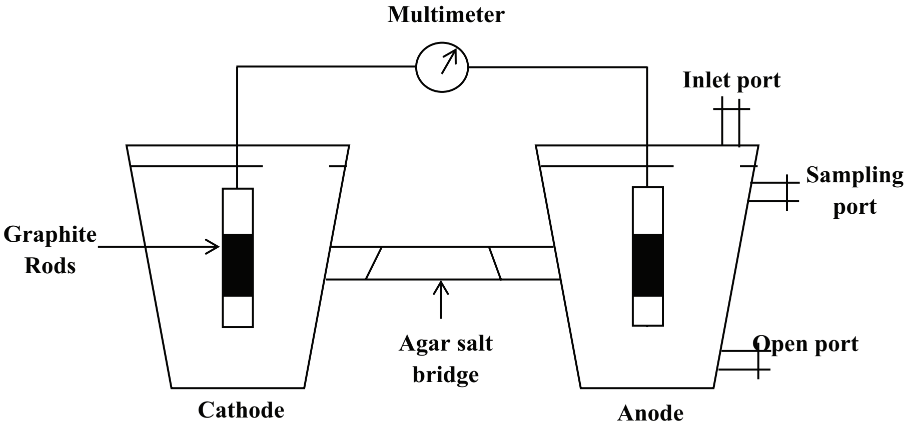

Fig. 7. Double chamber MFC.

Table 4
Greywater original sample characteristics

Characteristic	Batch condition	Semi-batch condition (100% concentrated)	Semi-batch condition (75% concentrated)
pH (alkaline)	7.6	7.4	7.9
Color	Grayish	Grayish	Grayish
Total dissolved solid (mg/l)	9010	9760	7400
BOD_5 (mg/l)	235.384	2368.92	1641.8
COD (mg/l)	3744	3872	2680
Current (mA)	0.28	0.31	0.18

6. Modeling the system

The ability to manage operation of PV, PEM fuel cells and electrolyzer is the most important in the system, which coordinate the changes load of house by time. PV operate throughout the presence of the radiation, but dealing with of the excess or missing power led to operate PEM fuel cells or electrolyzer by power management strategy that done by MATLAB function. The PV modules provides the necessary power to meet the total load demand, and the excess power from the PV modules will provides the electrolyzer to produce the hydrogen when $P_{PV} > P_{Load}$, but if $P_{PV} < P_{Load}$ then is necessary run PEM fuel cells to provide load of enough power to meet load demand. The manage operation of hybrid system as shown in Fig. 9.

The system is operated under several scenarios depending on the time throughout the day. First, at the morning (5:00 AM–8:00 AM). In this period of day the sun rise slowly and the solar radiation will increase slowly and the PEM fuel cell will operate partially to provide the lack of energy, because PV panels do not cover all demand of consumption as shown in Fig. 8. Second, at the time between (8:00 AM–8:00 PM). In this period of day, the solar radiation will increase to reach its maximum values. Thus, the power output from PV panels cover the load demand until the solar radiation decreases at sunset. Then PEM fuel cell still shutdown and work partially when sunset, but the excess of power from PV panels supply to electrolyzer to produce hydrogen as shown in Fig. 8. Third, at the time between (8:00 PM–5:00 AM). During this period, the solar radiation is zero so the power output from PV panels is zero. Thus, the demand load totally in this period is covered by PEM fuel cell until sunrise as shown in Fig. 10.

7. Conclusion

This study demonstrated that microbial fuel cell technology was able to treat greywater successfully, and microorganisms present in the wastewater allowed for electricity generation and COD and TDS removal. The performance of MFCs decreased with the decrease in the wastewater concentration. MFC technology will provide a new method to offset wastewater treatment plant in term of operating cost, making wastewater treatment more affordable for developing and developed nations. Thus, the combination of wastewater treatment along with electricity production will help in saving money for wastewater treatment and electricity generation. On

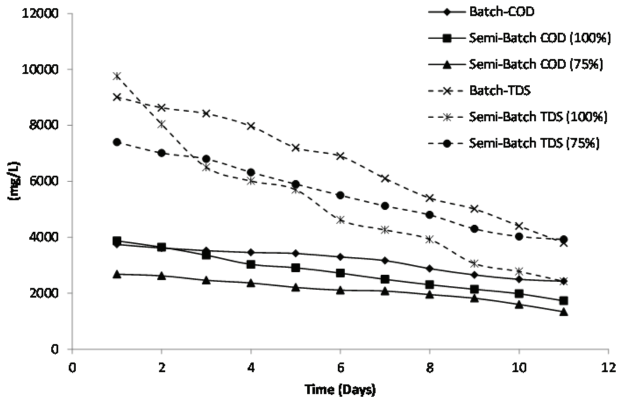

Fig. 8. COD and TDS during batch and semi batch condition.

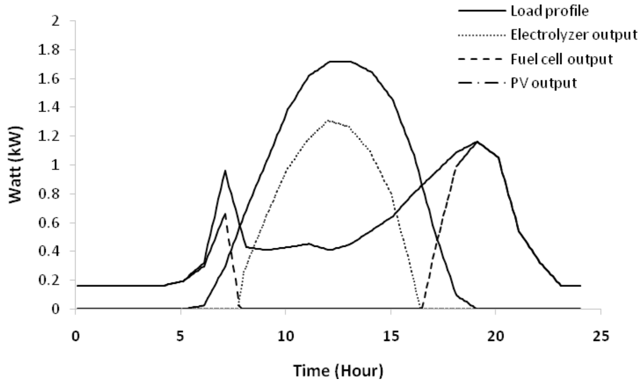

Fig. 10. PV, PEM Fuel Cell, load, electrolyzer during the day.

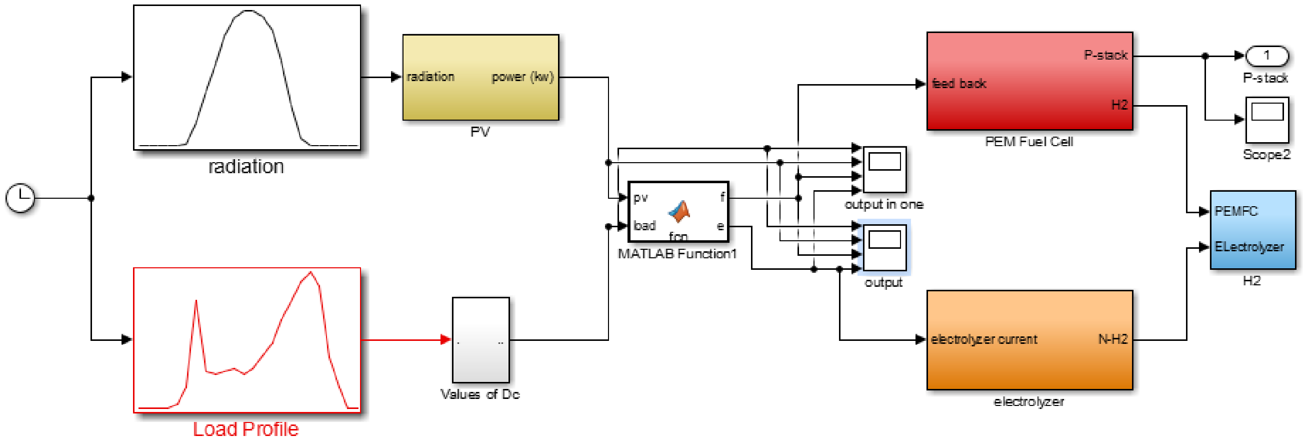

Fig. 9. The manage operation of hybrid system of PV, PEM fuel cell and electrolyzer.

the other hand, the study showed that it was possible to meet consumption demand for a house in Hebron City by using hybrid system PV with PEM fuel cell. However, the system was designed to meet the electrical needs of the house throughout the year, without any connection to the grid. It was found that the highest load consumption for the house was in January and then in July. Experiment showed that the system [at this scale] needed 18 PV panels of 260 W, 3 PEM fuel cells of 500 W, an electrolyzer of 1500 W, and hybrid inverter of 5 kW.

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