Hybrid renewable energy system for a remote area in UAE

Tareq Salameh
Sustainable and Renewable Energy Engineering
University of Sharjah
Sharjah, UAE
tsalameh@sharjah.ac.ae

Malek Alkasrawi
[2]Wisconsin Institute of Sustainable Technology, University of Wisconsin SP, WI, USA.
Malek.Alkasrawi@htu.edu.jo

Adel Juaidi
Mechanical Engineering Department
An-Najah National University
adel@najah.edu

Ramez Abdallah
Mechanical Engineering Department
An-Najah National University
ramezkhaldi@najah.edu

Sameh Monna
Architectural Engineering Department
An-Najah National University
samehmona@najah.edu

***Abstract*—**

The remote areas in the United Arab Emirates (UAE) doesn't have access to the electricity grid, therefore the standalone hybrid power system uses to provide the electrical power required to meet the demand in these areas. The components of the hybrid system were selected and optimized for this area instead of bringing the gird to this area based on the load profile for the appliance household in the area. Thousands of simulation trials were performed using HOMER Pro to achieve the best renewable fraction and Levelized cost of energy (LCOE). The LCOE was found 0.34 $/kWh after including the capital, recourses, operation and maintenance, and replacement cost for the lifetime of the project which is 25 years. The unmet electrical load and shortage capacity were 0.0102 % and 0.0912 %, respectively. Furthermore, the environmental impact of the system was compared with the diesel energy system based on the carbon footprint and emission as in carbon dioxide, carbon monoxide, unburn hydrocarbon, sulfur dioxide, and nitrogen oxide. The carbon footprint was 90.1 which equivalent to 1000 saving diesel gallons.

***Keywords*—Hybrid energy system, Solar PV, fuel cell, levelized cost of energy, renewable fraction**

I. INTRODUCTION

Conventional resources such as fossils fuels played a dominant role in the world energy system over the past decades [1-3]. The power plants, transportation, and industrial uses are the most energy applications required fossil fuel. Therefore, the depletion of fossil fuels increases year by year [1]. Besides the depletion issue, fossil fuels have a series impact on environmental degradation according to air pollution, ozone depletion that causes global warming due to the release of emission greenhouse gases and carbon dioxide (CO2) [2, 4]. Renewable energy is one of the alternative solutions for helping the issue of fossil fuel depletion [5-7]. Renewable energy is available in many forms based on the location of the place such as (solar, wind, hydro, biomass, geothermal, biomass, and fuel cell) [8, 9]. United Arab Emirates (UAE) has a good location in the Middle East and Arabian Gulf with a hot and dry climate [10]. The rate of energy

consumption in the UAE is very high due to the growing economy and population [11].

The UAE started implemented renewable energy technologies and reduce dependence on fossil fuel revenues [12]. Because the amount of global horizontal irradiance is high in UAE. Solar PV is one of the most important components in hybrid energy system. Shading effect is one of the big challenges for the solar PV performance [13, 14] Therefore, the use of a hybrid energy system is becoming crucial and important in order to reduce the depletion of fossil fuels and make a green environment [15].

In this paper, a stand-alone hybrid energy system based on solar photovoltaic (PV), fuel cell, electrolyzer, diesel generator (DG), , battery, and the converter was simulated by HOMER Pro software to evaluate the techno-economic and environmental aspects of the system.

II. METHODOLOGY

The hybrid energy system is spreading widely in the world due to the depletion of fossil fuels [16]. A hybrid energy system consists of conventional and renewable power supply components as solar PV, wind, diesel generator, biofuel generator, and fuel cell [15]. In addition to the combination of conventional and renewable resources, a hybrid energy system required an energy storage system based on electrical, thermal, hydraulic, and mechanical in order to mitigate inefficient power [18]. The selection of components for an off-grid hybrid energy system depends on the energy resources available in the remote area [19-21]. The different configurations of the hybrid energy system can be PV-Diesel generator-Battery, Wind-Diesel generator-Battery, PV-Wind-Diesel generator-Battery, PV-Wind-Diesel generator [22]. The fuel cell is one of the renewable energy systems [23]. A

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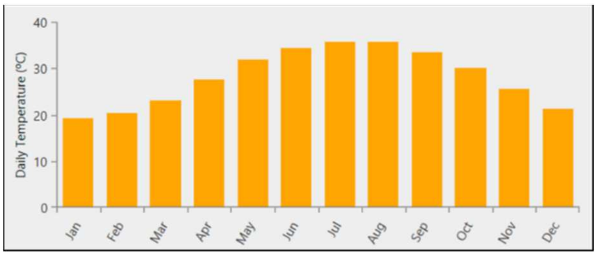
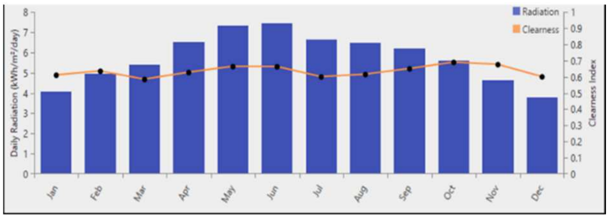
fuel cell has many types based on operating temperature, Solid oxide fuel cell (SOFC) works at high temperature [24] while proton exchange membrane fuel cell (PEMFC) works at low temperature [25,26]. The combination of solar photovoltaic PV and fuel cell one of the configurations of a hybrid energy system [27]. In the PV-Fuel cell hybrid system, the PV is used to derive the power to the electrolyzer to produce hydrogen, then the hydrogen production sends to the storage tank [28].

1. Weather conditions and load profile

Figure 1 shows the monthly average meteorological data for the United Arab Emirates (UAE) such as the temperature, solar radiation, and clearness index. The highest temperature was in August whereas the highest solar radiation was in June. The hourly daily load profile for appliance households is shown in Figure 2. Two peaks load is shown in Figure 2 at noon and 18 hours. The energy required for a single household is calculated according to the amount of energy required for the heating ventilation and air conditioning (HVAC) system and the consumer's use of some home electrical appliances. Table 1 shows all the energy needs for the air conditioning system and various household appliances.



(a)



(b)

Figure 1: Monthly average profile for (a) temperature (b) Solar radiation and clearness index.

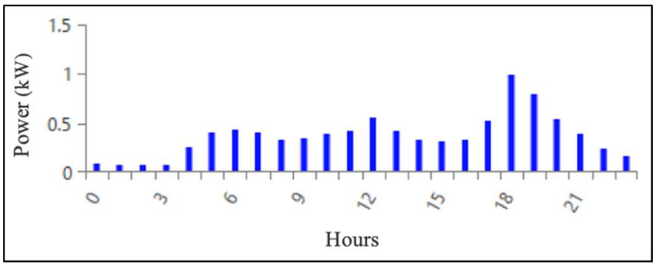


Figure 2: Daily electrical load profile for appliance household power consumption

Table 1: Energy required for a typical house in a remote area

Appliance	Energy per day (kWh)
Air conditioning system	27.39
Lights	6.02
Water heater	6
Refrigerator	1.75
Dishwasher	1.18
Television	0.8
Sprinkler	0.5
Fan (Window)	0.39
Coffee maker	0.35
Hairdryer	0.27
Microwave oven	0.24
Radio(stereo)	0.2
Iron	0.14
Vacuum cleaner	0.1
Clothes washer	0.08
Phone charger (5 phones)	0.07
Total	45.3

2. Hybrid system components

The components of the hybrid system are shown in Figure 3. The system consists of Solar Photovoltaic (PV), diesel generator (DG), fuel cell, electrolyzer, hydrogen tank, and converter. The details of each component are explained in the next sections

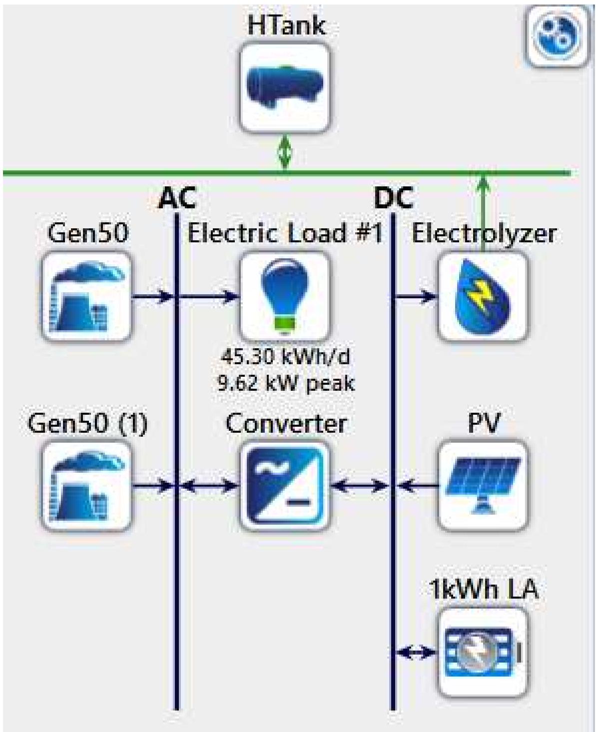


Figure 3: Solar PV, Fuel cell, battery and diesel generator hybrid system.

2.1. Solar photovoltaic

The power production from the PV array was calculated as presented in [5, 18, 19].

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}}\right) [1 + \propto_P (T_c - T_{c,STC})]$$

Where $T_{c,STC}$ is the PV cell temperature under standard test conditions (25°C), T_c is the PV cell temperature in the current time step (°C), $\propto_P$ is the temperature coefficient of power (%/°C) which is used to determine the effect of temperature. $\overline{G}_{T,STC}$ and $\overline{G}_T$ are the irradiance at standard test conditions (1 kW/m^2) and the irradiance on the PV array in the current time step (kW/m^2), f_{PV} is derating factor that used to considering the other parameters affect the PV array such as dust, soiling and bird waste and Y_{PV} is rated capacity of the PV array (kW).

2.2. Fuel Cell

Proton Exchange Membrane Fuel Cell (PEMFC) has strong functionality for start-up and shutdown with low operating temperature compared with other types of fuel cells. The hydrogen required for the electrochemical reaction (anode and cathode reaction) is produced by the electrolyzer which is delivered by power production from the PV array. The electrochemical reaction produces both electrical and thermal energy during the operation of the fuel stack. The electrical power produces by the fuel cell stack calculated as described in [17].

$$P_{FC} = U_{stack} I = U_{SC} N I$$

Where U_{stack} is the voltage of the stack. I is the current of the stack, U_{SC} is the average voltage of a single cell, and N is the number of cells. The efficiency of the stack can be calculated as presented in [17].

$$\eta = \frac{P_{FC}}{\dot{m}_{H_2} HHV_{H_2}}$$

Where P_{FC} is the stack power (W), $\dot{m}_{H_2}$ is the mass flow rate of the fuel (hydrogen) (kg/s), and HHV_{H_2} is the higher heating value of the fuel (120 MJ/kg).

2.3. Electrolyzer For Hydrogen Production

The power consumption by the electrolyzer was produced by the PV-Diesel generator, the power consumption was calculated using equation 5 as in [17].

$$P_{DC,EZ} = \frac{\dot{m}_{H2}\ HHV_{H2}}{h_{DC,EZ}}$$

Where $P_{DC,EZ}$ is the consumed DC power in electrolyzer (kW), $\dot{m}_{H2}$ is the mass flow rate of hydrogen (kg/s) and $h_{DC,EZ}$ is the efficiency of the electrolyzer. After the hydrogen generated by the electrolyzer, it will compress and be stored in the tank.

2.4. Diesel Generator

The diesel generator used in the system as backup, whenever there is a shortage in power production by the PV and fuel cell, the diesel generator starts working to meet the energy demand. While the excess of energy is used to charge the batteries and the diesel generator stopped.

2.5. Battery

The state of charge (SOC) of the battery was calculated as presented in [10, 22].

$$SOC_t = SOC_0 + \eta_c \sum_{k=0}^{t} P_{CB}(k) + \eta_d \sum_{k=0}^{t} P_{DB}(k)$$

Where SOC_t is the battery's SOC at any given time, SOC_0 is the SOC of the battery at initial time, P_{CB} and , P_{DB} are the charging and discharging power, respectively, η_c and η_d are the corresponding charging and discharging efficiency respectively.

The initial State of Charge is 100%, and the minimum State of Charge is 40%.

2.6. Power Converter

The bidirectional converter is working as an inverter to convert the direct current DC to alternating current AC and rectifier to convert the AC to Dc. The converting process depends on the power flow in the system. both capacity and efficiency were considered during the modeling and simulation as described in [17].

$$P_{Inv,Out} = P_{Inv,In} \eta_{Inv}$$

Where $P_{Inv,Out}$ is inverter output rated capacity, $P_{Inv,In}$ is Inverter input rated capacity and η_{Inv} is inverter efficiency.

3. Cost Analysis

3.1. Net Present Cost (NPC)

The life cycle cost of the system represents by the Net Present Cost (NPC). These costs include the total cost of the system components, replacement cost for the system components during the lifetime of the system, operation and maintenance cost, fuel cost, and the salvage cost of the components at the end life of the system [23 & 24]. the NPC was calculated as in the following equation: NPC is calculated by the following formula:

$$\text{NPC} = \frac{TAC}{CRF} \text{ or}$$

$$\text{NPC} = \frac{TCO(1+i)^N}{1+ROR}$$

Where TAC and TCO are the total annualized cost and the total capital outlay, respectively. TAC is the sum of capital cost, operation and maintenance cost, and salvage cost, respectively, while i, N, and ROR are the annual interest rate, the total number of years, and the rate of return of the investment. The capital recover factor (CRF) is calculated as follow;

$$\text{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Where n is the payback period in years (n).

3.2. Levelized Cost of Energy (LCOE)

The leveleized cost of energy (LCOE) is defined as the ratio between the total annualized system cost (ACS) to the system's yearly power output (E_{Total}) [23 & 24] as described in the following equation:

$$LCE = \frac{ACS}{E_{Total}}$$

Where the ACS is the net sum of the annualized capital, replacement and maintenance costs for all components in the hybrid energy system.

The LCOE can also be presented using the average generation cost (Cav) in ($/kWh) as in the next equation.

$$C_{av} = \frac{[CRF + m] \sum_{i=1}^{N} P_i R_i}{87.6 \sum_{i=1}^{N} R_i \, K_i}$$

Where m is the operation and maintenance cost (O & M) in ($/kWh), Pi is the ith generator capital cost ($/kW), Ri is the ith generator rating in kW, Ki is the load factor for i th generator.

The simulations were performed hour by hour with consistency with the hourly metrological data for the location. The simulations were repeated many times until the best Levelized cost of energy ($/kWh) and the renewable fraction achieved.

III. RESULTS AND DISCUSSION

The monthly average energy production for the solar PV-FC-DG-B is shown in Figure 4 (a). The energy productions were 90.6 %, 5.1%, and 4.28 % for the solar PV, fuel cell, and diesel generator, respectively. This can be explained because the location has abounded of solar radiation as shown in Figure 1 (b). Solar PV produces the energy for the conditioning system, household, and electrolyzer. The consumption power needs for the electrolyzer is around 3 kW as shown in Figure 4 (b). The power consumption by electrolyzer is used to produce hydrogen for fuel cell operation. If the fuel cells don't produce power then the hydrogen fills in the storage tank with a capacity 10 kg. the excess amount of electrical energy production by solar PV stored in the lead-acid battery. The diesel generator operates whenever there is a shortage in the energy production by solar PV to meet the demand for the house load as shown in the green region in Figure 4 (a).
Figure 5 (a) shows the diesel fuel consumption has the highest value during the winter months where the temperature is low as shown in Figure 1 (a) and the air conditioning doesn't need any energy. While in summer months, diesel consumes more fuel to meet the energy demand for the house.
On other hand, the amount of hydrogen storage is proportional to the optimum performance of the solar PV system during April and May months where the optimum operating temperature of Solar PV. The average monthly energy storage (state of charge (SOC)) in the battery is approximately the same for all months as shown in Figure 5 (c).

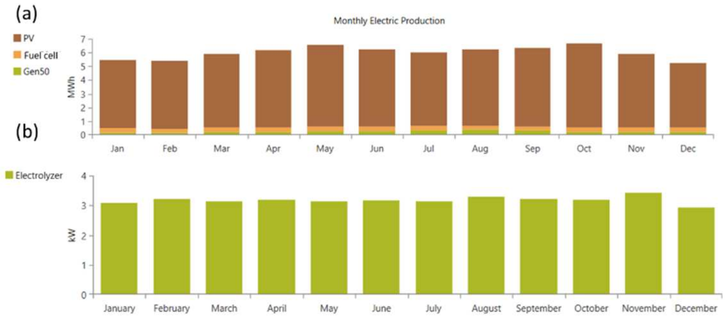


Figure 4: Average monthly (a) energy production by the system (b) power consumption by the electrolyzer

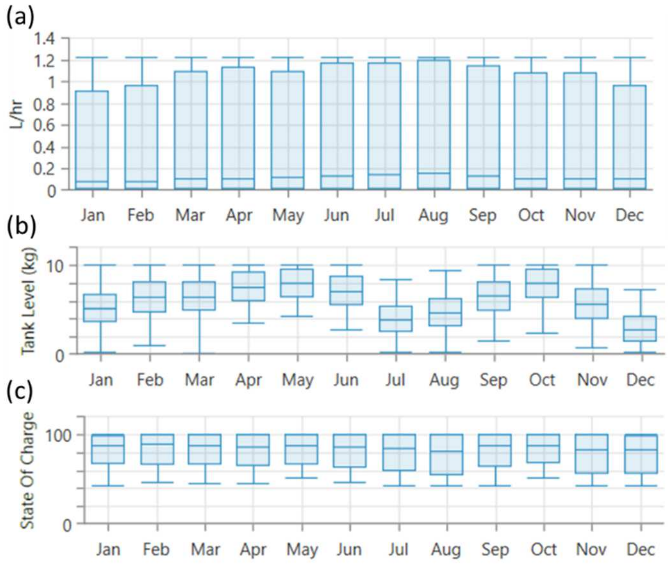


Figure 5: Average monthly (a) diesel fuel consumption (b) hydrogen level in the tank (c) state of charge of the battery

Figure 6 shows the hourly and daily mapping distribution for the diesel fuel consumption, level of hydrogen storage, and the state of the charge of the battery. Figure 6 (a) shows the highest fuel consumption occurs at 6 PM during the peak demand as shown in Figure 2. While Figure 6 (b) shows the level of the hydrogen in the tank was full during the summer due to the length of the daylight and during April and May where the optimum performance of the solar PV system was explained early. The state of the charge of the battery is shown in Figure 6 (c), the highest state of the charge appears afternoon during the fully charging process while the state of charge has the lowest value before the sunrise during the full discharge process.
The economic aspect for any hybrid energy system is represented by the cash flow. Figure 7 (a) and (b) show the cash flow based on the cost types and components. The capital and salvage costs appear at the beginning and the end of the lifetime of the system, respectively, as shown in Figure 7 (a) while the fuel and operation appear along the lifetime of the system. the replacement cost depends on the type of the components, for instance, some components change one per lifetime as in the diesel generator and convertor while the battery changes three times per the lifetime of the system as depicted in Figure 7 (b). The Levelized cost of energy (LCOE) was 0.34 $/kWh.

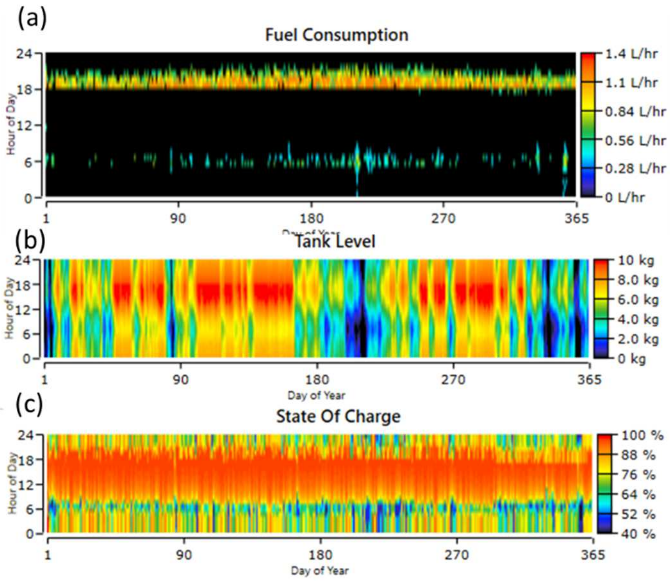


Figure 6: Daily and hourly mapping (a) diesel fuel consumption (b) hydrogen level in the tank (c) state of charge of the battery

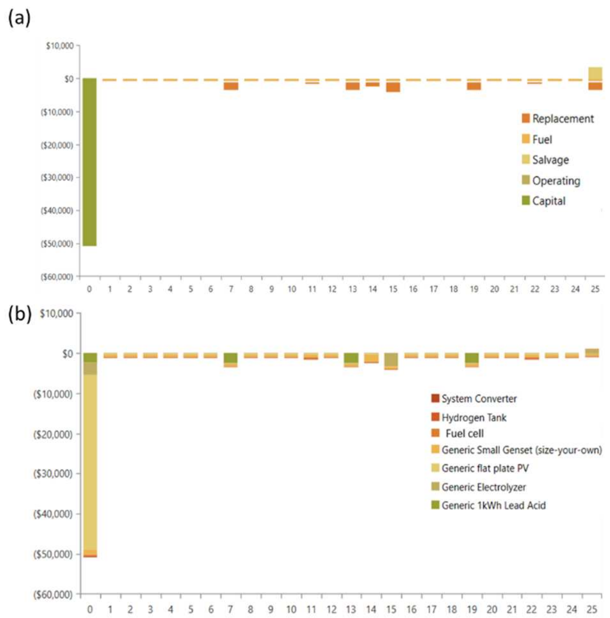


Figure7: Cash flow for the system based on (a) type of costs (b) components of the hybrid energy system

The environmental aspect of any energy system is measured by carbon footprint on the atmosphere. All the carbon footprint is due to the operation of a diesel generator according to the combustion process inside the engine. The details of the emission from the diesel generator are illustrated in Table 2 for the hybrid energy system and diesel generator only.

Table 2: Emissions from hybrid energy system and diesel generator system

Emission (kg/year)	Hybrid system	Diesel generator
Carbon Dioxide	2572	25982
Carbon Monoxide	35.2	164
Unburned Hydrocarbon	1.55	7.15
Particulate Matter	0.211	0.993
Sulfur Dioxide	6.37	63.6
Nitrogen Oxides	33.1	154

IV. CONCLUSION

A hybrid energy system based on solar PV, fuel cell, diesel generator, and battery for a remote location in UAE was simulated by HOMER Pro. The energy production from the hybrid energy system was met the thermal and electrical load demand for a single house. The levelized cost of energy was 0.34 $/kWh. The solar PV system contributed 90.6 % of total energy production by the hybrid system. The unmet electrical load was 1.69 kWh/year 0.0102 % and shortage capacity was 15.1 kWh/year 0.0912 %. The system reduced the carbon footprint by 90.1 % which equivalent to 1000 gallons of diesel.

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