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# Technico-economic analysis of off grid solar PV/ Fuel cell energy system for residential community in desert region

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ABSTRACT

A technico-economic analysis based on integrated modeling, simulation, and optimization approach is used in this study to design an off grid hybrid solar PV/Fuel Cell power system. The main objective is to optimize the design and develop dispatch control strategies of the standalone hybrid renewable power system to meet the desired electric load of a residential community located in a desert region. The effects of temperature and dust accumulation on the solar PV panels on the design and performance of the hybrid power system in a desert region is investigated. The goal of the proposed off-grid hybrid renewable energy system is to increase the penetration of renewable energy in the energy mix, reduce the greenhouse gas emissions from fossil fuel combustion, and lower the cost of energy from the power systems. Simulation, modeling, optimization and dispatch control strategies were used in this study to determine the performance and the cost of the proposed hybrid renewable power system. The simulation results show that the distributed power generation using solar PV and Fuel Cell energy systems integrated with an electrolyzer for hydrogen production and using cycle charging dispatch control strategy (the fuel cell will operate to meet the AC primary load and the surplus of electrical power is used to run the electrolyzer) offers the best performance. The hybrid power system was designed to meet the energy demand of 4500 kWh/day of the residential community (150 houses). The total power production from the distributed hybrid energy system was 52% from the solar PV, and 48% from the fuel cell. From the total electricity generated from the photovoltaic hydrogen fuel cell hybrid system, 80.70% is used to meet all the AC load of the residential community with negligible unmet AC primary load (0.08%), 14.08% is the input DC power for the electrolyzer for hydrogen production, 3.30% are the losses in the DC/AC inverter, and 1.84% is the excess power (dumped energy). The proposed off-grid hybrid renewable power system has 40.2% renewable fraction, is economically viable with a levelized cost of energy of 145 $/MWh and is environmentally friendly (zero carbon dioxide emissions during the electricity generation from the solar PV and Fuel Cell hybrid power system).



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## Introduction

The development of clean and renewable energy systems and new alternative fuels is needed to meet the future energy demand for power generation, commercial and residential buildings, transportation, and for industrial applications. The development, integration and the increase of the penetration of the renewable energy systems in the energy mix is needed because of the rapid growth of the world energy demand due to the population growth, the environmental impacts due to greenhouse gas emissions from fossil fuel combustion, and the depletion of the fossil fuels energy resources. A micro grid power system is an energy system that uses several energy resources including renewables (wind, solar, geothermal, biomass, hydro, and ocean); electrical generators using both fossil fuel and alternative and renewable fuels; energy storage systems; loads for residential, commercial and industrial applications; power converter units; and demand management and control system. The micro grid energy system can operate as grid-tied power system or off-grid (standalone) power system. The control functions for micro grid power systems will help to produce more energy independent from the grid, and provide backup to the utility grid, and security of the energy supply in case of emergency caused by major storms or natural disasters. The micro grid power system has many advantages for local community goals such as diversification of the energy sources, reduction of the carbon emissions by integrating renewable resources, reliability (generate, distribute and regulate the flow of electricity), resilience (reduce the impacts and damages of power outages in communities) and cost reduction.

Several studies can be found in the literature on micro grid power systems. A micro-grid model that integrates renewable energy sources such as micro hydro (MHP) and photovoltaic system (PV) is used in Ref. [1]. The hybrid renewable power system was connected to the grid. The results show the performances of the power plants with renewable energy sources were used with maximum efficiency. The micro-grid model with the largest capacity MHP produced the lowest energy cost, greatest reduction of $CO_2$ emissions, and largest fraction of renewable energy. However, these result required the expensive initial capital cost. In addition, the PV power generation was always recommended with a minimum capacity. A biomass-based PV power plant to supply the electrical power of agricultural wells was proposed in Ref. [2]. The results show that the combination of PV and biomass systems could be an effective way to make a reliable and cost-effective hybrid energy system. Hybrid technology combinations for electricity generation from a mix of renewable energy resources to satisfy the electrical needs were investigated in the past. Different renewable resources, namely, small-scale hydropower, solar photovoltaic systems, wind turbines, biodiesel generators and fuel cells were considered [3–9].

Simulation, modeling and optimization using HOMER software and Simulink [10–17] were also used to identify the optimal off-grid options. The results show that a hybrid combination of renewable energy generators at an off-grid location can be a cost-effective alternative to grid extension. Micro-power optimization model was used in Ref. [10] to design renewable energy-based micro grid system: solar-biomass hybrid system for the electrification of the city of Sharjah. Dynamic simulation was used in Ref. [12] to design PV-diesel-battery off grid power system. A switched model predictive control for energy dispatching of PV-diesel-battery hybrid power system was investigated in Ref. [13]. Simulink was used, in Ref. [14], for economic analysis and environmental impacts of hybrid PV-diesel-battery systems for remote villages. Different control strategies were used, in Ref. [15], and [16], for modeling hybrid PV-wind-engine-battery and PV-diesel-battery hybrid power systems, respectively.

A domestic microgrid solution composed of solar photovoltaic, metal hydride hydrogen-based storage with an electrolyzer, polymeric electrolyte fuel cell (PEM-FC), and interconnections with neighbor grids and electric vehicles was proposed by Ref. [18]. The simulated data from the proposed model was validated with experimental data for a pilot microgrid plant designed, built and operated by the authors. The theoretical and experimental role of Energy Management Strategies (EMSs) in hydrogen microgrid was studied by Ref. [19]. A set of different EMS performance in real-life was analyzed by new lab scale microgrid system. The authors studied and refined different controllers implemented for the obtaining dynamic models. The results show that how different control techniques influence the plant performance and a set of guidelines for designing and operating Smart Grids was provide. Feasible configuration of a solar-hydrogen integrated microgrid and the overall efficiency of a laboratory scale test facility were presented and characterized [20]. The experimental results show that the most significant inefficiencies are mainly attributed to the solar to electrical energy conversion process, which responsible for about 89% of losses. The overall conversion efficiency solar to hydrogen chain reached up to 5.3%. The main criteria for design, realization and validation of a solar-powered hydrogen fueling station in a smart city for on-site hydrogen production plant application was report by Ref. [21]. The hydrogen and electricity for an electric and hydrogen vehicles fleet were delivered by the plant. Four subsystems were used for hydrogen fueling station, these systems are hydrogen production system by electrolysis (alkaline electrolyzer), compression system, high -pressure storage system and hydrogen dispenser for automotive applications. Mebarki et al. [22] investigated the use of PEM fuel cell/battery storage system to supply electrical power for vehicle. Nasri et al. [23] developed autonomous hybrid system and coordinated intelligent management approach in power system operation and control using hydrogen storage.

The equipment modeling and simulation are relevant to critical topic of designing, manufacturing, energy management, economic analysis and optimal sizing. These topics are the main reasons for the development of many simulation tools in order to record the actual and real behavior of modern power plant and micro grid systems [24]. Distributed generation (DG) or micro grid power systems plays very important role in rural and remote areas because the difficult and uneconomical withdraw the power line over long distance [25]. Energy management using different control strategies and sizing method for stand-alone hybrid system based on photovoltaic solar panels, hydrogen subsystem and battery was presented by Ref. [26] using Simulink. Three different control strategies were applied, based on technical economic aspects.

The principal objective of this study is to design and test the performance a standalone hybrid renewable energy system (solar PV/Fuel cell) to meet the desired electrical load of 150 houses in the Emirate of Sharjah, United Arab Emirates. The parameters (dust accumulation and temperature) affecting the solar power output from the hybrid power system for the residential community located in the desert region are investigated in this study. The proposed power system should not only meet the daily and yearly energy consumption of the residential community but also provide high renewable fraction (increase the penetration of renewable energy in the energy mix), low excess power (reduce the dumped power), low levelized cost of energy and low environmental impacts (reduce the carbon dioxide emissions).

## Hybrid power system modeling

The proposed microgrid power system is based on a solar PV and hydrogen-based fuel cell generators to feed an AC load comprised of a residential community. The hydrogen, required to operate the fuel cell, is generated by an electrolyzer and stored in a tank. The electrolyzer is operated using the power generated from the microgrid. The DC to AC conversion is achieved by an inverter. The solar PV/Fuel cell hybrid renewable energy system is directly connected to DC bus to transfer the energy from the distributed generation to the inverter. The inverter converts the DC to AC power to satisfy the AC power demand of the residential houses. The DC bus is also used to satisfy the energy demand of the electrolyzer for hydrogen production. The microgrid and all components are shown in Fig. 1.

### *Photovoltaic array*

The PV power depends on the irradiance, the temperature and the characteristics of the PV array. The power output ($P_{PV}$) from the PV array is expressed as

$$P_{PV} = (N_s \times N_p) P_{m,STC} \left( \frac{G}{G_{STC}} \right) [1 + \alpha_P (T_c - T_{c,STC})] \tag{1}$$

where, $P_{m,STC}$ is the power of the PV module under standard test conditions (*STC*), $N_s$ is the number of modules, in series, in the string and $N_p$ is the number of strings in parallel, $G$ is the irradiance, $G_{STC}$ is the irradiance under STC ($G_{STC} = 1000$ W/m$^2$), $\alpha_P$ is the temperature coefficient of the power, $T_c$ is the PV module temperature, $T_{c,STC}$ is the PV module temperature under STC ($T_{c,STC} = 25\ ^\circ$C).

The PV system includes a DC-DC boost converter to match the PV voltage to the microgrid DC-bus. It has the following input-output relationship

$$V_{DC} = \frac{1}{1 - d} V_{PV} \tag{2}$$

where, $V_{DC}$ is the DC-bus voltage, $V_{PV}$ is the PV array voltage and $d$ is the duty cycle.

The duty cycle is carried out for the MPPT controller to extract the maximum power available from the sunlight.

The generated PV power ($P_{PV,gen}$) is affected by the weather and modules conditions (losses due to dust accumulation on the panel in the desert regions, shading, and degrading of the performance of the solar panels). Therefore, it is calculated using a derating factor ($f_{PV}$) such as

$$P_{PV,gen} = f_{PV} \times P_{PV} \tag{3}$$

The efficiency ($\eta_{PV}$) of the PV array is given by

$$\eta_{FC} = \frac{P_{PV,gen}}{G \times A} \tag{4}$$

where, $A$ is the area of the collector.

The monthly average solar global horizontal irradiance in Sharjah is illustrated in Fig. 2. The average monthly temperature profile was also included in this study (See Equation (1)). The high temperature in the desert region reduces the power output from the solar panel.

In order to assess the solar resource penetration, a factor, called renewable fraction, is used in the optimization of the micro-grid. It is the fraction of the energy delivered to the load that originated from the PV power source and is carried out using

$$f_{ren} = \frac{E_{PV,gen}}{E_{con}} \tag{5}$$

where, $f_{ren}$ is the renewable fraction coefficient, $E_{PV,gen}$ is the PV energy generation, $E_{cons}$ is the energy consumed by the load.

### *Fuel cell*

The fuel cell is a device that converts the fuel chemical energy into an electric energy. The device includes an anode, a cathode and an electrolyte. The conversion process is done through a chemical reaction in which the fuel is oxidized and electricity is generated. The output voltage ($V_{FC}$) of the fuel cell is given by fuel is oxidized and electricity is generated. The output voltage ($V_{FC}$) of the fuel cell is given by

$$V_{FC} = E - V_{act} - V_{\Omega} - V_{con} \tag{6}$$

where, $E$ is fuel cell internal voltage, $V_{act}$ is the activation voltage, $V_{\Omega}$ is the Ohmic voltage and $V_{con}$ is the concentration voltage.

The power ($P_{FC}$) generated by the fuel cell stack is given by

$$P_{FC} = N \times V_{FC} \times I_{FC} \tag{7}$$

where, $N$ is the number of cells in the stack series and $I_{FC}$ is the fuel cell current.

The electrical efficiency of the fuel cell is given by

$$\eta_{FC} = \frac{P_{FC}}{\dot{m}_{H_2} HHV_{H_2}} \tag{8}$$

where, $\dot{m}_{H_2}$ (kg/s) and $HHV_{H_2}$ are the mass flow rate and the higher heating value of the hydrogen fuel, respectively.

The fuel cell system includes a DC-DC boost converter to match the fuel cell voltage to the DC-bus voltage. Furthermore, the converter is controlled to provide the required

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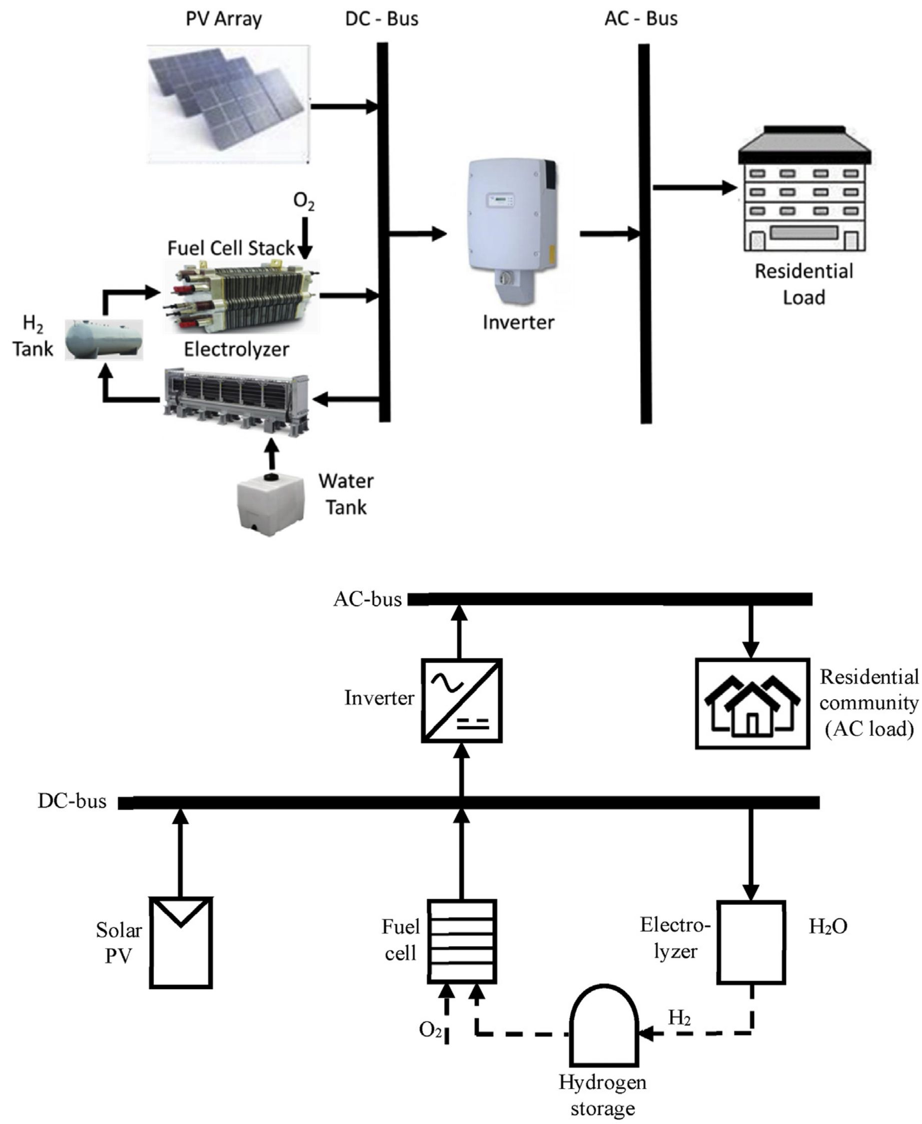


**Fig. 1 – Schematic of hybrid PV-Fuel Cell power system.**

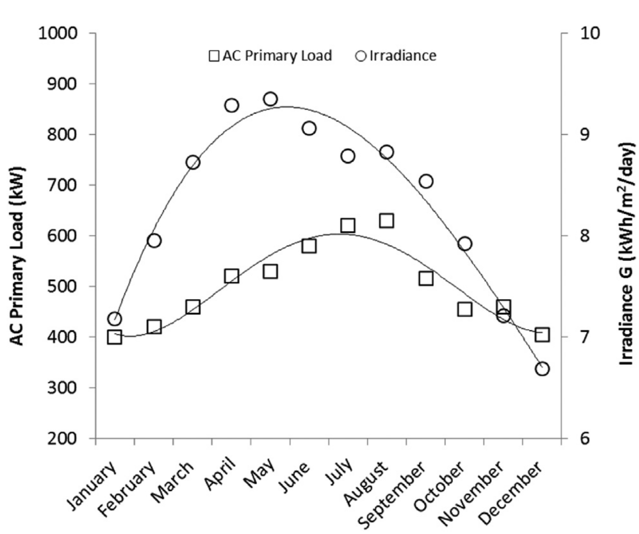


**Fig. 2 – Monthly average AC primary loads and solar horizontal irradiance G in Sharjah.**

power to meet the demand based on the control strategies to be discussed in Section Optimization and Control Strategies.

### *Electrolyzer for hydrogen production*

An electrolyzer consumes electricity to generate hydrogen via the electrolysis of water. The electrolysis is used for the decomposition of water into oxygen and hydrogen gas by passing an electric current through the water. The hydrogen produced is compressed and stored in the hydrogen storage tank to be used in the fuel cell for power generation or to serve a hydrogen load (external use) as shown in Fig. 1. The power consumption of the electrolyzer is given by

$$P_{EZ} = \frac{\dot{m}_{H_2} HHV_{H_2}}{\eta_{EZ}} \tag{9}$$

where, $P_{EZ}$ is the DC power consumed in the electrolyzer, $\dot{m}_{H_2}$ is the mass flow rate of the hydrogen produced (kg/s) in the electrolyzer, $HHV_{H_2}$ is the heating value of the hydrogen fuel (MJ/kg) and $\eta_{EZ}$ is the efficiency of the electrolyzer. A hydrogen tank is required to store the hydrogen produced by the electrolyzer for later use by the fuel cell. The model assumes that during the process of adding hydrogen to the tank, no electricity is used and the tank experiences no leakage.

The electrolyzer system includes a DC-DC buck converter to match the DC-bus voltage fuel cell voltage to the electrolyzer voltage. Furthermore, the converter is controlled to store the power excess based on the control strategy to be discussed in Section Optimization and Control Strategies.

### Converter

The connection between the DC-bus and the AC-bus of the microgrid is achieved by an inverter as shown in Fig. 1. The bus voltage and the frequency of the microgrid are regulated by the inverter.

The inverter is characterized by its rated power and efficiency, which is carried out by

$$\eta_{INV} = P_{AC}/P_{DC} \tag{10}$$

where, $\eta_{INV}$ is the inverter efficiency, $P_{DC}$ is the power at the DC-bus and $P_{AC}$ is the power at the AC-bus.

The inverter is controlled to maintain a constant DC-link voltage to meet the requirements of the load voltage. The control structure, depicted in Fig. 3, is based on proportional-integral (PI) control for CRTL blocks. It has an outer control loop to regulate the DC-bus voltage and an inner control loop to regulate the load current in order to ensure that the required power is transferred to the load.

### Load

The sizes of the solar PV and fuel cell power systems are based on the residential community loads. The AC load is specified by the power consumption of 150 houses in a residential community. The average daily energy consumption per house is 30 kWh/day. This is the average energy consumption in Sharjah and Dubai in the United Arab Emirates (It is noted that the energy consumption is high in the most of the emirates in UAE – Desert region). The average daily energy consumption for the 150 houses for the residential community is 4500 kWh/day. The monthly peak average power consumption of the residential community (AC primary load) was in August as shown in Fig. 2. In addition to monthly energy consumption, the daily energy profile (daily AC load) is needed for the simulation and modeling. A residential daily profile with maximum peak around 6 p.m. was selected. Examples of daily loads for the months of January, April, August and November are illustrated in Fig. 4.

The distributed generators (PV and Fuel Cell) supplies the power to the electrolyzer and the AC load demand ($P_L$) such as

$$P_{PV} + P_{FC} = P_L + P_{EZ} \tag{11}$$

To reduce the excess power $P_{ex}$, a hydrogen load with 16 kg of hydrogen per day for the residential community was added in the simulation (the excess power will be used to run the electrolyzer for hydrogen production to be used for other external use).

### Optimization and control strategies

An optimization analysis is used to find the best possible hybrid power system configuration based on the desired constraints at the lowest total net present cost. The performance index is the life-cycle cost or the levelized cost of energy ($/kWh). The cost of energy takes into account the capital cost, operation and maintenance cost, fuel cost, replacement cost and the revenue from the electricity generated [27]. To find the optimal possible configuration, a search space was created for each component (PV, Fuel Cell, Electrolyzer, Hydrogen Tank, and Converter) using the size of each component and a dispatch strategy. The size of each component (optimization search space) is given by:

- Solar PV Power Out Capacity (kW): lower limit = 0 and upper limit = 800.
- Fuel Cell Power Out Capacity (kW): 0, 700, 750, 800.
- Electrolyzer Power In Capacity (kW): 0, 250, 300, 350.
- Hydrogen Tank Capacity (kg): 0, 850, 900, 950.
- Inverter (kW): lower limit = 0 and upper limit = 800.

Many different system configurations were simulated to find the feasible solutions to satisfy the desired constraints. The calculations were performed for each simulation time step (30 min), which represents 17,520 simulations per year.

Dispatch Control Strategies: In this work, two dispatch control strategies were used in the operation of the off grid solar PV-Fuel Cell hybrid energy system: Load following strategy (LF) and Cycle charging strategy (CC). In LF strategy, the main objective is to meet the load demand (the solar PV is used only to feed the primary load). If the solar PV cannot meet the load demand, the fuel cell will operate at a rate that provides only enough power to meet the energy demand. In CC strategy, the fuel cell will operate at full power rate in order to meet the load demand and the surplus is used to run the electrolyzer for hydrogen production. The two control strategies LF and CCdiffer in the method of operating the fuel cell. The flow-chart, presented in Fig. 5, shows the feasible solutions or configurations of the hybrid power system to satisfy the desired constraints and using the two proposed dispatch control strategies LF and CC (see Fig. 6).

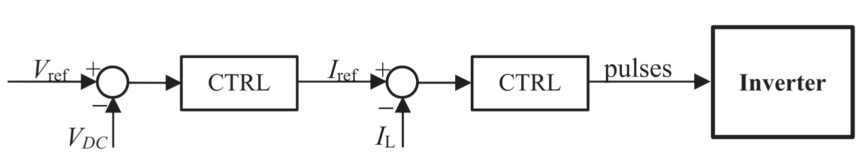


**Fig. 3 – Control scheme for the inverter.**

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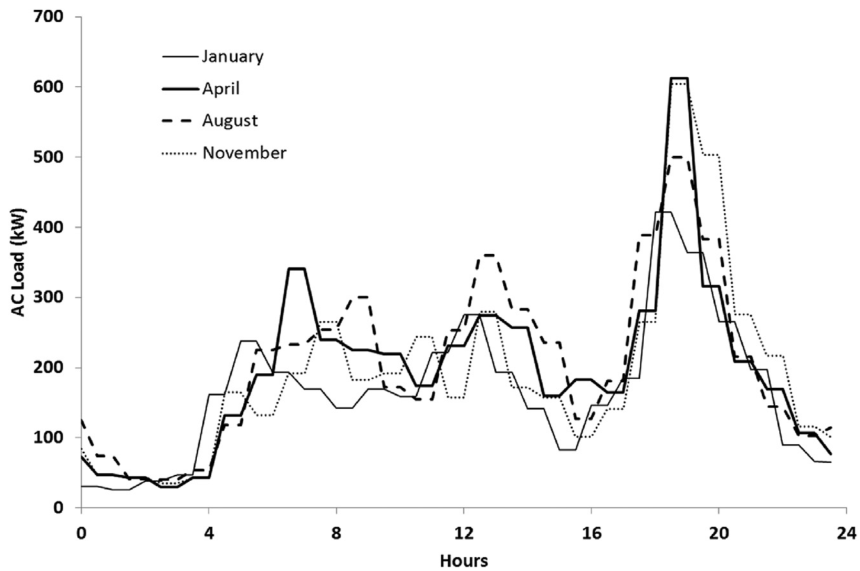


**Fig. 4 – AC primary load daily profiles.**

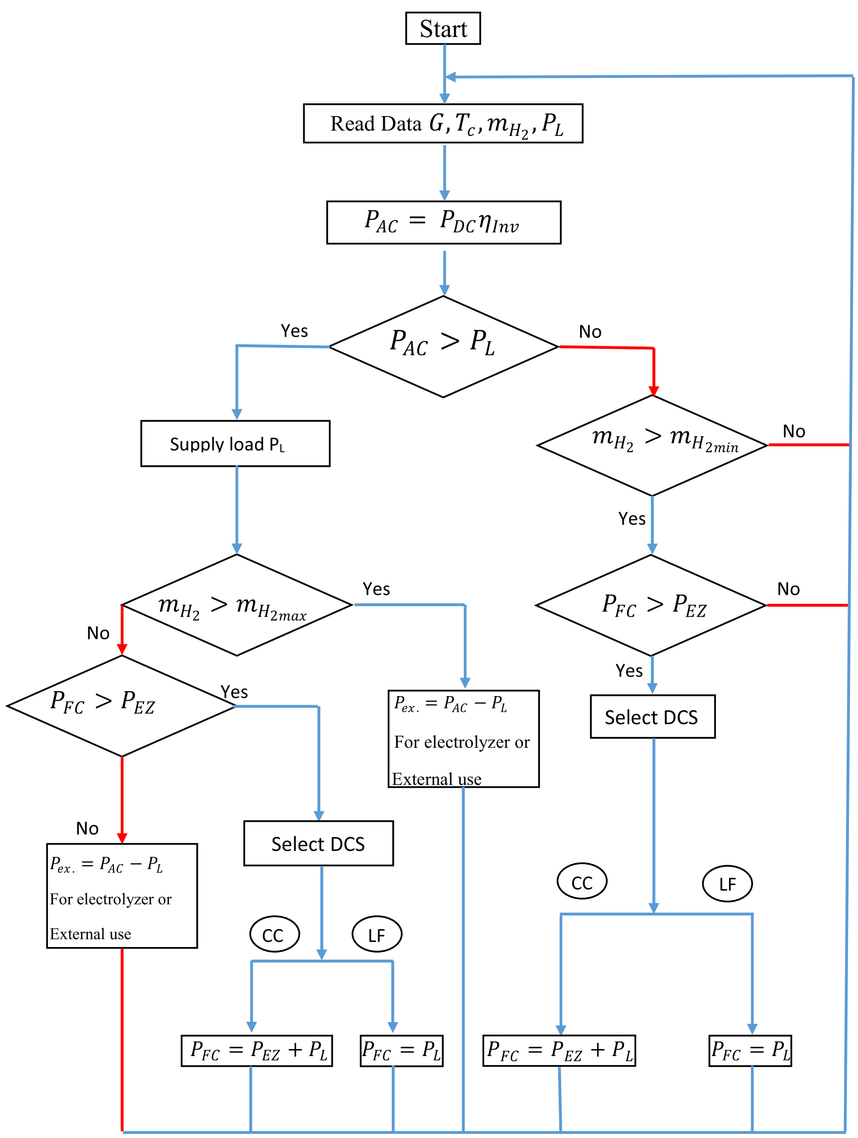


**Fig. 5 – Power management system of the off grid hybrid power system.**

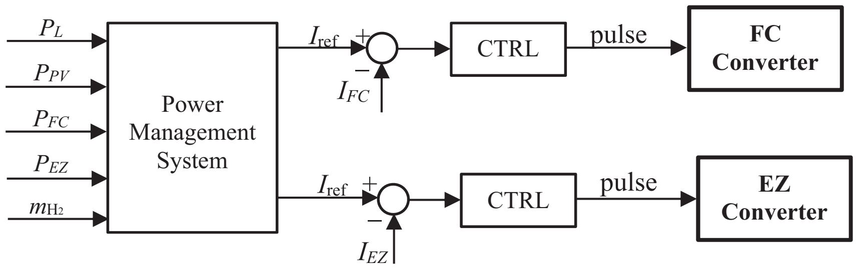


**Fig. 6 – Control system for the fuel cell and electrolyzer converters.**

The power management system, based on the above dispatch control strategies, provides the current references to discharge the fuel cell and store the hydrogen through electrolyzer as shown in Fig. 5. These references will be used in the current control loops to control the fuel cell and the electrolyser converters.

## Hybrid system components and sizing

The hybrid off grid power system is composed of solar flat PV system, fuel cell, electrolyzer, hydrogen tank, converter, and controller. A description of the selected parts for the hybrid power system (components and sizing) is summarized as:

- **Solar PV**: Type: Canadian Solar Max Power CS6U-330; Module: polycrystalline; Nominal Maximum Power ($P_{max}$ = 330 W); Operating Voltage $V_{mp}$ = 37.5 V; Operating Current $I_{mp}$ = 8.80 A; Open Circuit Voltage $V_{OC}$ = 45.9 V; Open circuit Current $I_{SC}$ = 9.31 A; Efficiency = 16.97%; Operating Temperature 45 °C, Derating factor $f_{PV}$ = 75%, and the Life time = 25 years. The cost for the solar PV systems is given by: Capital = $1300/kW, replacement = $1300/kW, and Operation and Maintenance (O&M) = $5/year/kW.
- **Fuel Cell**: Type - PEM Fuel Cell (DC); Electrical efficiency ηFC = 70%; Fuel: Hydrogen and the Life time (hours) = 50,000. The cost for the Fuel Cell is given by: Capital = $600/kW, Replacement = $600/kW, O&M = $0.01/hour/kW.
- **Electrolyzer**: Type - Generic Electrolyzer (DC); Efficiency ηEZ = 90%, Life time = 15 years. The cost of the Electrolyzer is: Capital = $150/kW, Replacement = $150/kW, and O&M = $8/year/kW.
- **Hydrogen Tank**: Life time = 25 years and the cost of the hydrogen tank per 1 kg: capital = $0.5/kg, replacement = $100, O&M = $10/year/kg, and hydrogen fuel cost = $1/kg.
- **Converter (inverter)**: Type - Leonics S219CPH; Voltage = 48 VDC; Efficiency = 96%; Life time = 25 years. The cost per 1 kW: Capital = $40/kW, Replacement = 40$/kW, O&M = 10$/year/kW.

The effects of temperature on the performance of the PV system were also included in this study. The performance of the PV system decreases with (1) an increase of the ambient temperature (high temperature in summer in the Sharjah – the monthly average temperature is Sharjah was included in the simulation) and (2) the accumulation of the dust on the solar panels (The derating rate of 75% was selected for this study).

## Results and discussions

The results of the modeling, simulation and performance of the standalone hybrid solar PV/Fuel cell power systems for the residential community in Sharjah are presented in this section. The simulation results include (1) the production of electricity from the PV array and Fuel cell, (2) the power consumption by the AC primary load for the residential community and the electrolyzer input DC power, (3) the power losses in the converter (DC/AC inverter), (4) the off grid energy system excess power (dumped power), (5) the unmet AC load (power shortage), (6) the annual pollutants emitted by the power system, (7) the cost summary of the power system (capital, fuel, operation and maintenance (O&M) replacement and salvage), and (8) the cash flow for the life of the system. The daily and monthly average electrical production, and the net present cost over the life (25 years) of the hybrid power system are presented in this paper. The hybrid power system was designed to meet the energy demand of 150 houses of the residential community in Sharjah that represent 4500 kWh/day. The calculations were performed for each simulation time step (30 min), which represents 17,520 simulations per year. Thousands of simulations and optimization were performed to calculate the energy to and from each component. An optimization analysis is used to find the best possible hybrid power system configuration based on the desired constraints at the lowest net present cost. The optimized results based on the lowest cost of energy COE of the hybrid power system were obtained using the optimization search space (see optimization and control – Part Section Optimization and Control Strategies). The best configuration was obtained with a combination of 517 kW PV array, 750 kW Fuel Cell, 250 kW electrolyzer, 900 kg Hydrogen tank, 738 kW inverter and using a cycle charging (CC) control strategy.

The results of the best configuration are presented in details this paper. The rated capacity of the PV system is 517 kW but the mean power output from the PV array is 117 kW with 4386 h per year of operation. This represents a mean output of 2817.86 kWh/d and a capacity factor of 22.72%. For the Fuel cell the maximum electrical output (rated capacity) is 750 kW but a mean electrical power output of 167 kW was produced from the fuel cell with a fuel consumption of 43,965 kg of hydrogen per year. The fuel energy input is 1,465,493 kWh/year and the electrical production from the fuel cell is 999,200 kWh/year. This represents an electrical efficiency of 68% for the fuel cell. The rated capacity of the inverter is 738 kW but a mean power

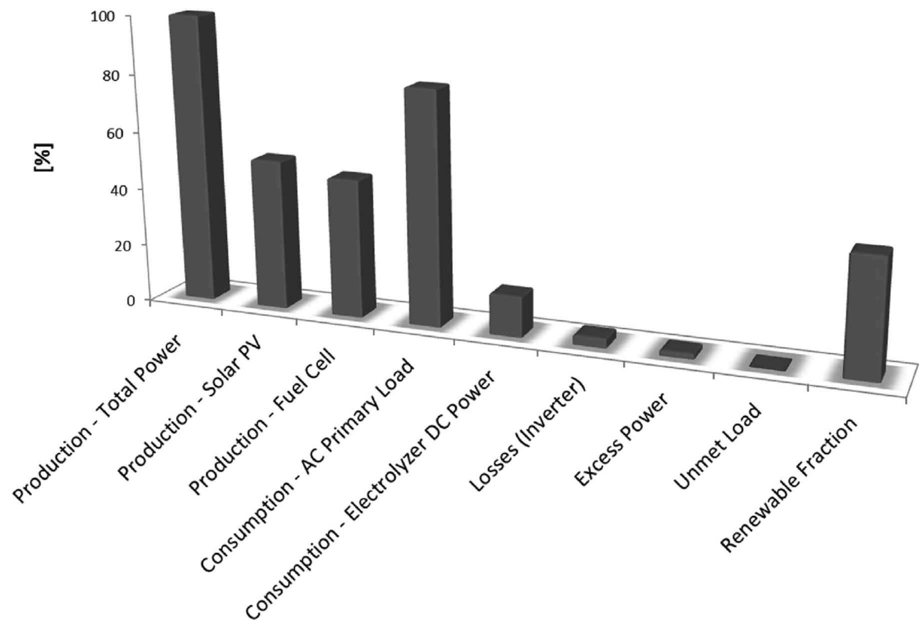


**Fig. 7 – Energy production, consumption, losses, excess electricity, unmet load and renewable fraction of the hybrid solar PV/Fuel cell power system.**

output of 187 kW was used by the inverter. This represents a capacity factor of 25% for 8760 h per year of operation. The energy in for the inverter is 1,709,337 kWh/year and the energy out is 1,640,964 kWh/year. The inverter power losses are 68,373 kWh/year.

The total electrical production from the hybrid power system is 2033 MWh/year with 1052.68 MWh/year from the PV system (52%) and 980.32 MWh/year from the Fuel Cell (48%) as shown in Fig. 7. This represents a renewable fraction (See Equation (5)) of 40.2%. The proposed hybrid power system meets the AC primary load of 1640.87 MWh/year (80.70% of the total production) with a small percentage of unmet load (1.63 MWh/day or 0.08%) as shown in Fig. 7. The hybrid system is also used to power the electrolyzer 286.37 MWh/year (14.08%) for hydrogen production, and produces some excess power 37.53 MWh/year (1.8%) that will be damped (see Fig. 7). The system power losses are 68.37 MWh/year (3.30%) that represents the power losses in the converter during the conversion from DC to AC power (see Fig. 7).

Figs. 8 and 9 show the daily performance of the fuel cell and elctrolyzer. Fig. 8 shows an example of the fuel cell electrical production and the DC power required to run the elctrolyzer during three days (August 15–17). It is noted that the capacity of the fuel cell is 750 kW and the maximum peak electrical production from the fuel cell for these three days is between 500 and 750 kW. The electrical production from the fuel cells is mainly early in the morning and during the night where there is no solar radiation. The capacity of

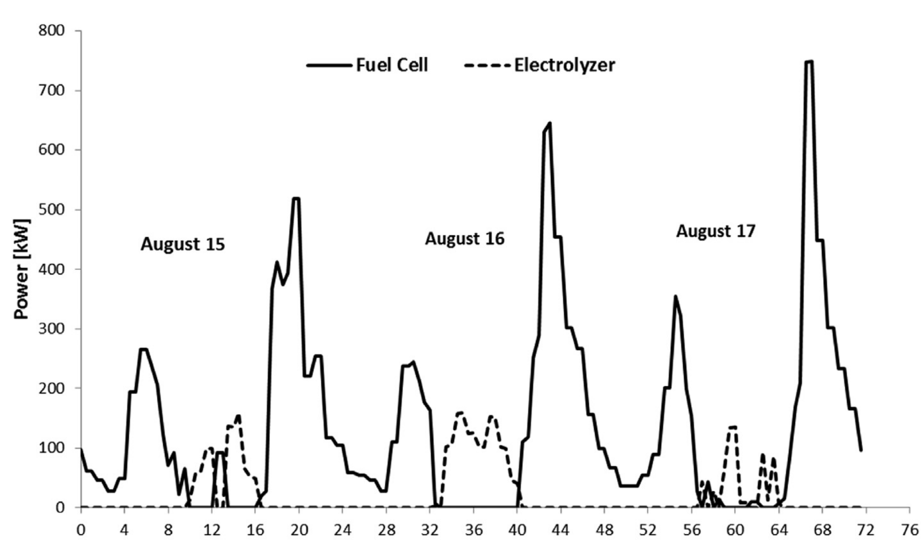


**Fig. 8 – Electrolyzer power consumption and fuel cell power production.**

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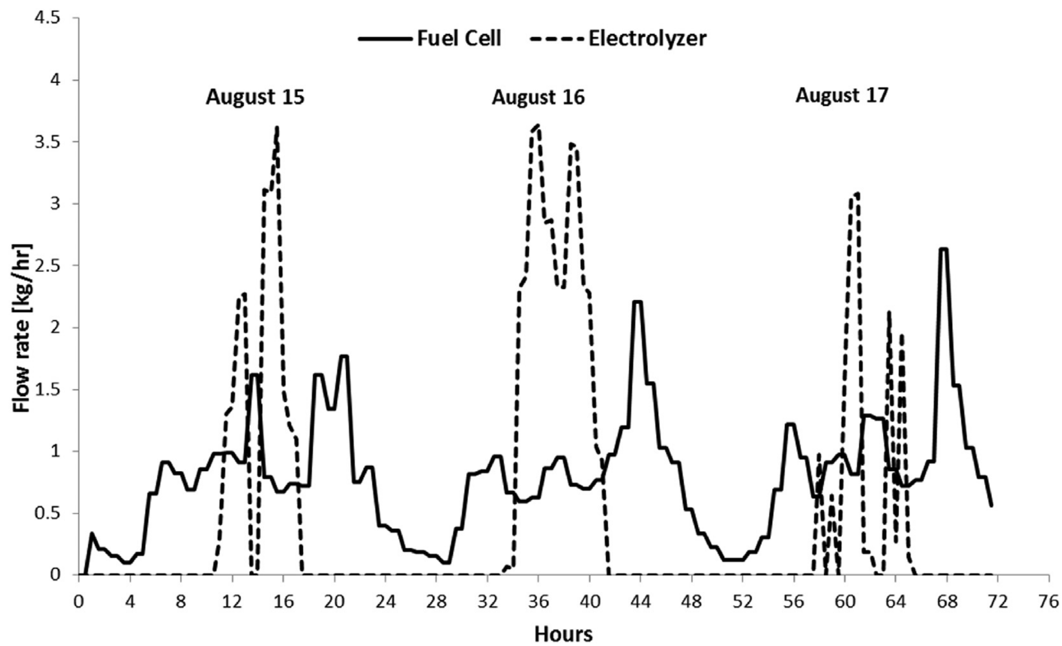


Fig. 9 – Electrolyzer hydrogen production and fuel cell hydrogen fuel consumption.

the electrolyzer is 250 kW and the maximum peak DC power consumed by the electrolyzer during the three days in August is about 160 kW. It is also noted that the power consumed by the electrolyzer is during the day. The excess power from the solar PV will be used to run the electrolyzer. Fig. 9 shows the mass flow rate of hydrogen consumed by the fuel cells to produce electrical power and produced in the electrolyzer.

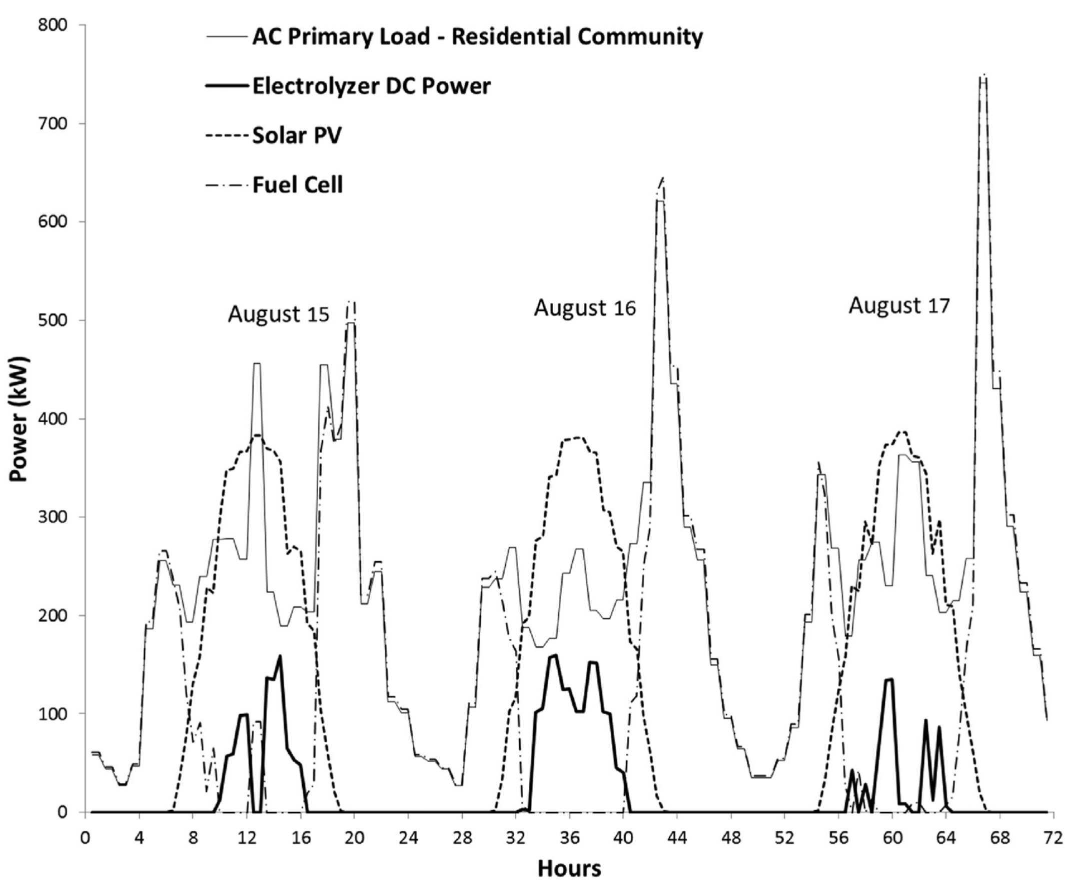


Fig. 10 – Daily performance of the hybrid solar PV/Fuel Cell power system for 72 h (August 15, 16 and 17).

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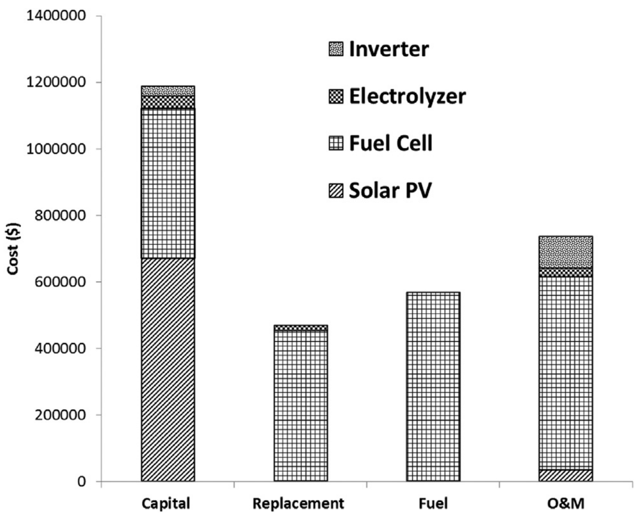


**Fig. 11 – Cost summary - PV/Fuel Cell hybrid power system.**

Fig. 10 shows the performance of the hybrid Solar PV/Fuel Cell power system. The results show the AC primary load, the DC power needed to run the electrolyzer for hydrogen production and the power production from the PV and fuel cell for 72 h (August 15, 16, and 17) in August where the energy consumption is high. The results show that most of the power production during the day is from the solar PV and during the night from the fuel cell. Most of the AC primary load for the residential community is met through the hybrid system. The excess power from the PV system during the day is also used to run the electrolyzer.

A summary of the capital, replacement, fuel, and operation and maintenance costs for the hybrid solar PV/Fuel Cell power system is shown in Fig. 11. The highest cost $1.19 Million is for the capital cost of the solar PV/Fuel Cell/Electrolyzer/Inverter system (57% for the PV system and 38% for the Fuel Cell). The total net present cost is $3.07 Million and the levelized cost of energy of the hybrid system is 145 $/MWh.

## Conclusions

Optimized design and control strategies were used in this study to design a hybrid off grid power system to meet the electric loads of 150 houses in Sharjah (residential community in a desert region). The effects of high temperature and the dust accumulation on the solar panels on the performance and the design of hybrid off grid power system are included in the present study. The micro grid hybrid power system includes two power generators (solar PV and fuel cell) integrated with electrolyzer for hydrogen production and DC/AC Inverter. A technical-economic analysis was used in this study to test the daily performance and the cost of the proposed hybrid micro grid power system. The results show that the solar PV/Fuel Cell/Electrolyzer/Inverter power system meets the daily electrical demand of the selected 150 houses in the residential community. A detailed analysis was performed in this study on the proposed standalone hybrid renewable energy system in the desert region: total energy production and the contributions from the solar PV and Fuel cell; the energy consumption: AC primary load and the electrolyzer for hydrogen production; the energy losses in the inverter; the excess power in the system; unmet load; renewable fraction, $CO_2$ emissions reduction and the leveled cost of energy. The solar PV/Fuel Cell off-grid power system integrated with solar based electrolyzer offers a very good penetration of renewable resources (renewable fraction $f_{ren} = 40.2\%$), low levelized cost of energy (145 $/MWh), low excess power (1.8%) and produce zero carbon dioxide emissions during the electricity generation.

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