Optimized design and control of an off grid solar PV/hydrogen fuel cell power system for green buildings

C Ghenai1,3 and M Bettayeb2

1Department of Sustainable and Renewable Energy Engineering, University of Sharjah, PO Box 27272, Sharjah, United Arab Emirates
2Department of Electrical and Computer Engineering, University of Sharjah, PO Box 27272, Sharjah, United Arab Emirates

E-mail: cghenai@sharjah.ac.ae

Abstract. Modelling, simulation, optimization and control strategies are used in this study to design a stand-alone solar PV/Fuel Cell/Battery/Generator hybrid power system to serve the electrical load of a commercial building. The main objective is to design an off grid energy system to meet the desired electric load of the commercial building with high renewable fraction, low emissions and low cost of energy. The goal is to manage the energy consumption of the building, reduce the associate cost and to switch from grid-tied fossil fuel power system to an off grid renewable and cleaner power system. Energy audit was performed in this study to determine the energy consumption of the building. Hourly simulations, modelling and optimization were performed to determine the performance and cost of the hybrid power configurations using different control strategies. The results show that the hybrid off grid solar PV/Fuel Cell/Generator/Battery/Inverter power system offers the best performance for the tested system architectures. From the total energy generated from the off grid hybrid power system, 73% is produced from the solar PV, 24% from the fuel cell and 3% from the backup Diesel generator. The produced power is used to meet all the AC load of the building without power shortage (<0.1%). The hybrid power system produces 18.2% excess power that can be used to serve the thermal load of the building. The proposed hybrid power system is sustainable, economically viable and environmentally friendly: High renewable fraction (66.1%), low levelized cost of energy (92 $/MWh), and low carbon dioxide emissions (24 kg CO₂/MWh) are achieved.

1. Introduction
The rapid growth of the world energy demand has raised concerns over the heavy environmental impacts (climate change and global warming due to greenhouse gas emissions from fossil fuel combustion), depletion of the energy resources (fossil fuels – coal, oil and natural gas) and future energy supply shortage. Clean and renewable energy systems and the development of alternative fuels are needed to meet the future energy demand for buildings, transportation, and industrial sectors [1]. The energy consumption for both residential and commercial buildings has increased steadily for the last years and has reached an average of 40% - 50% of the total energy consumptions. In some countries, the energy consumption for buildings has exceeded the energy consumptions for other sectors such as transportation and industrial applications. In 2016, and based on the U.S. Energy Information Administration (EIA) estimates, about 40% of the total U.S. energy consumptions was consumed by residential and commercial sectors. In the United Arab Emirates in particular and Gulf
Cooperation Countries located in the desert region, the energy consumption for building can reach 80% (mainly energy consumption from air conditioning system) of the total energy consumption [2]. This upward trend in energy demand in building will continue in the future due to the population and economic growth, the increase in the demand of the building services and comfort level and new building construction boom. The building sector has a key role to play when it comes to energy efficiency and the development and integration of renewable energy systems.

One way to increase the share of renewable energy in the energy mix is the development of micro grid power systems. Micro grid power systems use different types of renewable energy resources (wind, solar, biomass, hydro); energy generators powered with fossil, alternative or renewable fuels; energy storage devices; loads for residential, commercial and industrial applications; electric vehicles charging stations; and power conditioning units such as inverters and rectifiers. The micro grid energy system can be connected to the utility grid or can operate separately off grid as stand-alone power system. The locally controlled micro grid power system provides more independence from the grid, a backup to the utility grid and security of the energy supply in case of emergency caused by major storms and natural disasters, offers more reliability of the energy supply and reduces the transmission losses. Several studies can be found in the literature on the use of micro grid power systems for different applications [3-7]. Simulation, modeling and optimization using HOMER software (Hybrid Optimization Model for Electric Renewable) and Simulink [8-13] have been used to identify the optimal off-grid options.

The focus of this study is the use of micro-grid energy system to power commercial building. Fossil fuel was the primary fuel used to generate electricity for buildings. New energy systems using renewable energy resources (solar, wind, biomass, and biofuels) can be used as alternative to the conventional fossil fuel based power systems. A building powered by renewable energy systems is more sustainable solution to the high energy consumption for building (use of renewable resources – no depletion of natural resources; clean energy systems – reduction of GHGs emissions; reduction of the operational costs – use of natural resources). Hazem et al [14] used optimal design of stand-alone hybrid photovoltaics and fuel cell power system without battery storage to supply the electric load demand of the city of Brest in France. The study focused on the economic performance and is mainly based on the loss of the power supply probability concept. The Homer based simulation and optimization study showed that the hybrid power systems based on solar PV and fuel cells are a viable alternative to diesel generators. The fuel cell generator can efficiently complement a fluctuating renewable resource such as solar or wind to satisfy the energy demand of the city. Simulation of the operation of the PV-wind-fuel cell system was performed by Attala et al. [15]. The system architecture was based on 40 KW PV, 2 wind turbine, 6 KW Fuel cell, 10 KW Converter, and 10 kW electrolyzer. HOMER software was used to size and optimize the hybrid system. The results showed that the combination of Solar PV/Fuel cell and wind turbine is viable solution to meet the energy demand.

The principal objective of this study is to model, simulate, and optimize the design of an off grid hybrid power system based on solar PV and fuel cell in order to meet the desired electric load of the commercial building. The goal is to design a stand-alone renewable power system with high renewable fraction (increase the penetration of renewable resources for the energy mix), low levelized cost of energy and with low environmental impacts (reduce the carbon dioxide foot print).

2. Stand-alone hybrid power system modeling
The off grid hybrid power system, shown in table 1 consists of a solar PV array, Fuel Cell, Electrolyzer for hydrogen production, tank for the storage of compressed hydrogen, backup generator, energy storage system or battery bank and converter (DC/AC inverter). The proposed hybrid system is used to meet the building AC load. The building AC load is based on the building energy consumption from the air conditioning system, lighting and other equipment (see figure 1). The proposed hybrid off grid power system is modeled as follows:
Table 1. Hybrid power system components and specifications.

| System Component | Description |
|------------------|-------------|
| **Solar PV**     | **Type:** Canadian Solar Max Power CS6U-330 with maximum power capacity $P_{PV}\text{max} = 1200 \text{kW}$  |
|                  | **Module:** polycrystalline, Nominal Maximum Power = 330 W, Operating Voltage $V_{mp} = 37.5 \text{V}$, Operating Current $I_{mp} = 8.80 \text{A}$, Open Circuit Voltage $V_{OC} = 45.9 \text{V}$, Open circuit Current $I_{SC} = 9.31 \text{A}$, Efficiency = 16.97%, Operating Temperature 45°C, and Derating factor $f_{PV} = 80\%$  |
|                  | **Cost per 1 kW:** Capital = $1200/\text{kW}$, Replacement = $1200/\text{kW}$, O&M = $3/\text{year}$  |
|                  | **Life time** = 25 years  |
| **Fuel Cell**    | **Type:** PEM Fuel Cell (DC) with Maximum Power Capacity $P_{FC}\text{max} = 200 \text{kW}$  |
|                  | **Fuel:** Hydrogen, Electrical Efficiency $\eta_{FC} = 70\%$  |
|                  | **Cost per 1 kW:** Capital = $400/\text{kW}$, Replacement = $400/\text{kW}$, O&M = $0.01/\text{hour}$  |
|                  | **Life time (hours)** = 50,000  |
| **Electrolyzer** | **Type:** Generic electrolyzer (DC), Efficiency $\eta_{EZ} = 90\%$ with Maximum Power Input Capacity $P_{EZ}\text{max} = 200 \text{kW}$  |
|                  | **Cost per 1 kW:** Capital = $100/\text{kW}$, Replacement = $100/\text{kW}$, O&M = $8/\text{year}$  |
|                  | **Life time** = 15 years  |
| **Hydrogen Tank**| **Type:** Hydrogen tank with a Maximum Capacity of 200 kg.  |
|                  | **Cost per 1 kg:** Capital = $0.5/\text{kg}$, Replacement = $100/\text{kg}$, O&M = $10/\text{year}$, Hydrogen fuel cost = $1/\text{kg}$  |
|                  | **Life time** = 25 years  |
| **Backup Generator** | **Type:** Genset, Electrical AC bus with Maximum Power Capacity $P_{BG}\text{max} = 100 \text{kW}$,  |
|                  | **Fuel:** Diesel, HHV = 43.2 MJ/kg, density = 820 kg/m$^3$, Minimum Load Ratio = 25%.  |
|                  | **Cost per 1 kW:** Capital = $300/\text{kW}$, Replacement = $300/\text{kW}$, and O&M = 0.01 $/\text{hr}$. Diesel Fuel cost = $0.6/\text{liter}$  |
|                  | **Life time (hours)** = 15,000  |
| **Battery**      | **Type:** Lead Acid Battery 1 kWh, Voltage = 12 V, 4 batteries in series: 12 x 4 = 48 V with a Maximum of 1200 strings in parallel.  |
|                  | **Cost per 1 kWh:** Capital = $200/\text{kWh}$, Replacement = $200/\text{kWh}$ per battery, O&M = $5/\text{year}$. Lifetime = 12.5 years  |
| **Converter:**   | **Inverter/Rectifier** Leonics S219CPH with Maximum Power Capacity of $P_{In/Rect}\text{max} = 1200 \text{kW}$  |
| System Component | Description |
|------------------|-------------|
| Voltage = 48 VDC, Efficiency = 96% |
| Cost per 1 kW: Capital = $40, Replacement = 40$, O&M = 10$/year |
| Lifetime = 25 years |

Figure 1. Hybrid power system.

2.1. Solar PV array
The power output \( P_{PV} \) from the PV array is expressed as

\[
P_{PV} = P_{PV,STC} f_{PV} \left( \frac{G}{G_{STC}} \right) \left[ 1 + \alpha_p (T_c - T_{c,STC}) \right]
\]  

where, \( P_{PV,STC} \) is the power output under standard test conditions (STC), \( f_{PV} \) is the PV derating factor (accounting for power reduction due to soiling of the panels, wiring losses, shading, and aging), \( G \) is the current irradiance, \( G_{STC} \) is the irradiance under STC, \( \alpha_p \) is the temperature coefficient of the power, \( T_c \) is the PV module temperature, and \( T_{c,STC} \) is the PV module temperature under STC. The standard test
conditions (STC) are: $G_{\text{STC}}=1000\,\text{W/m}^2$, $T_{c,\text{STC}}=25^\circ\text{C}$, and no wind.

The efficiency of the PV module (conversion of the sunlight into electricity at its maximum power point under standard test conditions) is given by:

$$
\eta_{m,\text{STC}} = \frac{P_{m,\text{STC}}}{A_{PV} G_{\text{STC}}}
$$

where $A_{PV}$ is the surface area of the PV module [m$^2$].

### 2.2. Fuel cell

The fuel cell converts chemical fuel to electricity through a chemical reaction in which the fuel is oxidized and electricity is generated. The fuel cell is modeled as a power generator with hydrogen as the main fuel stored in hydrogen tank. Part of the consumed chemical fuel power which is not converted into electric power ($P_{\text{FC}}$) is converted to thermal stack power ($P_{\text{FCT}}$).

The electric stack power $P_{\text{FC}}$ is the product of stack voltage and stack load:

$$
P_{\text{FC}} = U_{\text{Stack}} I = U_{\text{SC}} N I
$$

where $U_{\text{SC}}$ is the average single cell voltage and $N$ is the number of cells.

The electrical efficiency of the fuel cell (conversion of the chemical energy in the hydrogen fuel into electricity) is given by:

$$
\eta_{\text{FC}} = \frac{P_{\text{FC}}}{m_{H_2} \text{HHV}_{H_2}}
$$

where $m_{H_2}$ (kg/s) and HHV$^{H_2}$ are respectively the mass flow rate and the higher heating value (HHV = 120 MJ/kg) of the hydrogen fuel.

### 2.3. Electrolyser 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 as shown in figure 1. The power consumption of the electrolyzer is given by:

$$
P_{\text{EZ}} = \frac{m_{H_2} \text{HHV}_{H_2}}{\eta_{\text{EZ}}}
$$

where $P_{\text{EZ}}$ is the DC power consumed in the electrolyzer, and $\eta_{\text{EZ}}$ is the efficiency of the electrolyzer. A hydrogen tank is needed to store the hydrogen produced by the electrolyzer for later use in a hydrogen-fueled generator or fuel cell. The model assumes that during the process of adding hydrogen to the tank, no electricity is consumed and the tank experiences no leakage.

### 2.4. Battery bank

The charge or the discharge power into or out of the battery is regulated by the output power from the hybrid generation system (Solar PV and Fuel Cell) and the load demand at a given time. At any time, the battery state of charge (SOC) is expressed as follows

$$
\text{SOC}(t) = \text{SOC}(0) + \eta_c \sum_{k=0}^{t} P_{\text{cha}}(k) + \eta_d \sum_{k=0}^{t} P_{\text{dis}}(k)
$$

Where, SOC(0) is the initial SOC of the battery, $P_{\text{cha}}$ is the charged power, $P_{\text{dis}}$ is the discharged power, $\eta_c$ is the charging efficiency, $\eta_d$ is the discharging efficiency. It is noted that a battery string or bank...
comprises a number of cells/batteries connected in series to produce a battery or battery string with the required usable voltage/potential e.g. 6 V, 12 V, 24 V, 48 V, 110 V.

2.5. Generator
The generator is the back-up power supply to be used in case the load demand cannot be satisfied by the PV array, Fuel Cell and the battery bank. The generator power output is function of the fuel consumption and is modeled by means of a linear equation:

\[ F_{BG} = \alpha_0 P_{BGR} + \alpha_1 P_{BG} \]  

(7)

where \( F_{BG} \) is the generator fuel (Diesel, Biodiesel, Biogas, Natural gas, etc...) consumption (l/hr), \( \alpha_0 \) is the generator fuel intercept coefficient (L/hr/kW\text{rated})), \( P_{BGR} \) is the rated capacity of the generator (kW), \( \alpha_1 \) is the generator fuel curve slope (L/hr/kW\text{Output}) and \( P_{BG} \) is the power output (kW) from the generator. The electrical efficiency of the generator is the ratio of the electrical energy coming out divided by the chemical energy of the fuel going in (product of the fuel mass flow rate and the higher heating value of the fuel HHV).

2.6. Converter
The converter is connected between the DC-bus and the AC-bus as shown in figure 1. It has a bidirectional operation depending on the power flow, where it works as an inverter to transfer the power from the PV array, battery bank (discharge) and Fuel Cell to the AC load, and as a rectifier in case of charging the battery bank from the backup generator. The converter is modeled based on its rated capacity (\( P_{Inv} \)) and efficiency (\( N_{inv} \)), which are assumed to be constant throughout its operating range. Furthermore, its rated DC voltage specifies the number of PV modules and batteries in each string of the PV array and the battery bank, respectively.

\[ P_{InvOut} = P_{InvIn} \eta_{Inv} \]  

(8)

2.7. Load
The power AC load is specified by the power consumption of the building (Air Conditioning System, Lighting, Equipment, etc...). The PV array, fuel cell, battery bank, and the backup generator are used to supply the electrical demand of the building.

2.8. 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. To find the optimal possible configuration, a search space was created for each component (PV, Fuel cell, Electrolyzer, Battery, backup Generator, Converter and hydrogen tank) using the size of each component (lower and upper capacity limits) and the dispatch strategy. 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 (60 minutes), which corresponds to 8760 simulations per year.

Two dispatch or control strategies were selected for this study: the load following (LF) and cycle charging (CC). In the load following strategy, the generator will operate only to meet the primary demand load. The renewable power sources are used to charge the storage bank. In the cycle charging, the generator will operate at maximum capacity to meet the demand load and the surplus of electrical production is used to charge the battery and run the electrolyzer.

In the combined design optimization and control strategies of the hybrid power system, the fraction of the solar energy and other renewable resources from the total generated energy is specified by the renewable fraction (\( f_{ren} \)) coefficient calculated by

\[ f_{ren} = 1 - \frac{E_{nonren}}{E_{cons}} \]  

(9)

where, \( E_{nonren} \) is the nonrenewable energy production, and \( E_{cons} \) is the total energy consumed by the load.
3. Load profiles, renewable resources and hybrid power system component selection and sizing

3.1. Daily and seasonal profiles of the building

The University of Sharjah administration building is used as a case study for the proposed stand-alone hybrid power system. This Building is 18 years old and has a total area of approximately 14,092 m². The building consists of four floors (ground floor plus three levels). The AC load is specified by the energy (kWh) or power (kW) consumption of the building as shown in figures 2 and 3. An energy audit has been performed at selected buildings at the University. The results of the energy audit showed that the energy consumption of the administration building at the University of Sharjah is 80% from the air conditioning system, 10% lighting and 10% for other equipment. The University of Sharjah is located in Sharjah City in the United Arab Emirates. This is a desert region where the air conditioning system is running most of the time during the year. The energy consumption is mainly related to the cooling of the building. The average energy consumption per day is about 6,540 kWh based on the results of the energy audit. In addition to the seasonal profile shown in figure 2, the daily average profile is needed for the hourly simulation of the performance of the hybrid system. The daily average power consumption for four days (January 15, April 15, July 15, and November 15) is shown in figure 3.

![Figure 2. Monthly AC primary load profiles (Year 2015) and Solar Irradiance G.](image)

![Figure 3. Daily AC primary load profiles.](image)

3.2. Renewable resources

The monthly average solar global horizontal irradiance in Sharjah is illustrated in figure 2. The annual average solar radiation in Sharjah is 8.30 kWh/m²/day. The solar radiation is available throughout the year, therefore considerable amount of solar power output can be generated using solar PV to serve the load of the building.

3.3. Hybrid power system components and sizing

The hybrid off grid power system is composed of solar flat PV system, fuel cell, electrolyzer, hydrogen fuel tank, backup generator, battery bank, converter (DC/AC inverter), and controller. A description of the selected parts for the hybrid power system is summarized in table 1. 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 Sharjah – Desert region) and (2) the accumulation of dust on the solar panels. The accumulation of dust on the solar panel and its effect on the power produced was included in the derating factor \( f_{PV} \).
4. Results
The simulation results include the production (Solar PV array, Hydrogen Fuel Cell and Backup Diesel Generator) and the consumption of electricity by the system (primary loads of the building and Electrolyzer for hydrogen production), the annual pollutants emitted by the power system, and cost summary (capital, fuel, operation and maintenance O&M, replacement of the parts of the system and salvage). 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 the commercial building that consumes 6,540 kWh/day. Thousands of hourly simulation and optimization runs were performed to calculate the energy to and from each component. The optimized results based on the lowest cost of energy (LCOE) of the hybrid power system were obtained using the optimization search space. The simulation and optimization methodology is based on the microgrid power system model selected in this study. Based on the selected design configuration (Solar PV, fuel cell, and back generator), search space (maximum power capacity off each component) and the daily power load requirement for the building, the simulation is performed for each hour of the year to investigate the technical feasibility and life cycle cost. In the optimization process, simulation of different configurations (single component such as solar PV only or combination of two or more components such as solar PV/fuel cell or solar PV/fuel cell/generator) is carried out to find the most appropriate system configuration that satisfies the technical constraints and the lowest life cycle cost. Based on this simulation and optimization methodology, the best three configurations (System 1, System 2 and System 3) exhibiting the lowest cost of energy are described in what follows: first configuration (System 1) uses two renewable systems (Solar PV and Fuel Cell) and one backup generator using Diesel or fossil fuel. The second configuration (System 2) uses only renewable and clean energy systems (Solar PV and Fuel Cell) to generate electricity. The third one (System 3) uses Solar PV in combination with Diesel generator (fossil fuel power system). Table 2 summarizes the energy production, consumption, the excess energy, the energy lost in the system (battery and inverter), and the unmet load for the three systems. It is noted that based on the results of the simulations and the technical constraint (lowest cost of energy), all the three systems use the cycle charging control strategies for the power generation (the generator will run at maximum capacity to meet the AC primary load and the excess power is used for the power input of the electrolyzer and to charge the battery). The results show that System 1 offers the lowest solar PV (1,025 kW), storage (267 strings in parallel) and inverter (864 kW) system capacities compared to the systems 2 and 3.

The total electrical production from the hybrid power system (system 1) is 3,055.95 MWh/year with 2,247.88 MWh/year from the PV system (73.6%), 723.22 MWh/year from the Fuel Cell (23.7%) and 84.85 MWh/year (2.7%) from the backup Diesel generator. The hybrid power system (system 1) meets all the AC primary load of 2,384.75 MWh/year for the building but also produces some excess power (557.06 MWh/year) that can be used to meet the thermal load of the building (the thermal load of the building was not included in the present study). The mean power output from the PV array is 257 kW with 4,345 hours per year of operation. This represents a mean output of 6,159 kWh/d and a capacity factor of 25%. A mean electrical power output of 118 kW was produced from the fuel cell with hydrogen fuel consumption of 31,821 kg/year, 6142 hours per year of operation, and a mean electrical efficiency of 68%. The backup Diesel generator produced a mean electrical power of 88 kW with 28,505 kg/year of Diesel fuel consumption, 967 hours per year of operation and 30% thermal efficiency. For the energy storage, the nominal capacity is 1,068 kWh (string size of 4 and 267 strings in parallel). The energy in for the battery bank is 69,640 kWh/year and the energy out is 55,713 kWh/year. This represents 13,928 kWh/year of loss through the battery bank. The inverter capacity was 864 kW but the mean power output from the inverter was 263 kW. This represents a capacity factor of 30% for the 8,760 hours per year of operation. The energy in for the inverter is 2,385,728 kWh/year and the energy out is 2,299,899 kWh/year. The inverter power loss is 95,829 kWh/year. The optimized hybrid Solar PV/Fuel Cell/Generator/Battery/Inverter power system produces 3,055.95 MWh/year. From the total energy produced from the hybrid system, 78.1% is used to meet the AC primary load of the building, 18.2% is the excess power (can be used to meet the thermal load of the
building). 3.6\% is the system losses in both the battery bank during charging and discharging process and the inverter (conversion form DC to AC power), and 0.08\% is the unmet load. The renewable fraction of the hybrid power system (system 1) is 66.1\%. Figure 4 shows a comparison between the three systems of the total energy production from the solar PV, Fuel cell, and Diesel generator; the energy consumption (AC primary load of the building), the losses in the battery and inverter, the unmet load and the renewable fractions. For the daily performance of the system, the results show that during the day most the energy is produced from the PV system where the solar irradiance is high and during the night most of the energy is produced from the fuel cell.

**Table 2.** Comparison of the energy production and consumption, excess energy, systems losses and unmet load for the three systems.

| Production Consumption Losses | System 1 Solar PV Fuel cell Backup Generator | System 2 Solar PV Fuel cell | System 3 Solar PV Backup Generator |
|---|---|---|---|
| Total production | 3,055.95 MWh/year (100\%) | 3,154.10 MWh/year (100\%) | 3,207.008 MWh/year (100\%) |
| Solar PV | Maximum Power 1.025 MW | Maximum Power 1.077 MW | Maximum Power 1.2 MW |
| Production | 2,247.88 MWh/year (73.60\%) | 2,359.786 MWh/year (74.31\%) | 2,630.391 MWh/year (82\%) |
| Fuel Cell | Maximum Power 200 kW | Maximum Power 200 kW | No |
| Production | 723.22 MWh/year (23.70\%) | Production = 794.381 MWh/year (25.19\%) | |
| Backup Generator | Maximum Power = 100 kW | No | Maximum Power = 100 kW |
| Production | = 84.85 MWh/year (2.7\%) | | Production = 576.817 MWh/year (18\%) |
| AC primary Load | 2,389.1 MWh/year (78.10\%) | 2,389.1 MWh/year (75.70\%) | 2,389.1 MWh/year (74.50\%) |
| Excess Power | 557.05 MWh/year (18.22\%) | 633.2 MWh/year (20.07\%) | 675 MWh/year (21.04\%) |
| System losses - Battery and Inverter | 109.9 MWh/year (3.59\%) | 131.2 MWh/year (4.16\%) | 140.78 MWh/year (4.38\%) |
| Unmet Load | 2.35 MWh/year (0.08\%) | 2.306 MWh/year (0.07\%) | 2.378 MWh/year (0.07\%) |
A comparison study was performed concerning the performance and the cost of the hybrid power systems for the best three Systems (see table 3). It is shown clearly from these results that system 1 with Solar PV/Fuel Cell/Generator/Battery offers the best option with respect to the cost of energy (92 $/MWh). The system offers a high renewable fraction (66.1\%) and is the second rated with respect to the carbon dioxide emissions (24 kg CO\(_2\)/MWh). The system will meet all the energy demand for the building with 18.2\% excess electricity that can be used for the thermal load of the building. A summary of the capital, replacement, fuel, and operation and maintenance costs for the PV/Fuel Cell/Diesel Generator/Battery/Inverter hybrid power system was also determined. The initial total capital of the hybrid power system (system 1) is $1.54 Millions ($1.23 Millions for the PV system) with a payback period of 6.83 years. The cost of energy (COE) for the proposed system is 92 $/MWh.

| Systems                                      | Cost of Energy ($/MWh) | Renewable Fraction (%) | Excess Electricity (%) | CO\(_2\) Emissions (kg/MWh) |
|----------------------------------------------|------------------------|------------------------|------------------------|-----------------------------|
| Base line system (grid – fossil fuel power system) | 120                    | 0                      | 0                      | 632                         |
| 1: Solar PV/Fuel Cell/Generator/Battery/Inverter | 92                     | 66.1                   | 18.2                   | 24                          |
| 2: Solar PV/Fuel Cell/Battery/Inverter       | 99                     | 66.7                   | 20.1                   | 0                           |
| 3: Solar Generator/Battery/Inverter          | 169                    | 75.8                   | 21                     | 157.6                       |

5. Conclusions
Simulation, modelling and optimization were performed in this study to design a hybrid off grid power system to meet the electric loads of a commercial Building (Administration Building at the University of Sharjah). The micro grid hybrid power system includes solar PV, fuel cell, electrolyzer, backup generator, battery bank and inverter. The building AC primary loads, solar resources in Sharjah, the
technology options, component cost, and constraints were determined. An integrated optimization design and control strategy was used to test the performance and the cost of the proposed hybrid micro grid system. The results show that the solar PV/Fuel Cell/Generator/Battery/Inverter off grid power system meets the yearly electrical demand of the selected building. The proposed hybrid system offers the best option for power generation compared to the other system architectures. The hybrid power system based on solar PV and hydrogen fuel cell offers the best penetration of renewable resources (66.1% renewable fraction), low levelized cost of energy (92 $/MWh), and low carbon dioxide (CO₂) emissions (24 kg CO₂/MWh).

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