International Conference on Renewable Energies and Power Quality (ICREPQ'14)
Cordoba (Spain), 8th to 10th April, 2014
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.12, April 2014

Employing Hydrogen Fuel Cell in Hybrid Energy Systems for Stand-Alone, Off-Grid Remote Sites in UAE

Ensiyeh Keshtkaran, Abbas A. Fardoun and Hassan Noura

Department of Electrical Engineering
United Arab Emirates University
P.O. Box 15551, Al-Ain, UAE

E-mail: **Ensiyeh.ksht@yahoo.com, afardoun@uaeu.ac.ae, hnoura@uaeu.ac.ae**

Abstract. In this paper, the economic feasibility of Proton Exchange Membrane Fuel Cell (PEMFC) as part of a stand-alone renewable energy system for a remote application in UAE is examined and investigated.

HOMER (computer software simulation tool) was used to conduct the analysis for sizing and optimization. The study takes into account the load requirement variations, capital cost (FC, PV and diesel generator cost) and running cost (Hydrogen, PV cleaning, and diesel cost). The costs are based on the location of interest. In addition, equivalent circuit model of the fuel cell system is developed based on experimental data. Simulated results matches the experimental data very well at steady state conditions.

Key words

Hybrid Energy System, Hydrogen Fuel Cell, Reliable Backup Power Source, Independent Renewable Energy.

1. Introduction

The reverberating cadence of diesel generators producing electricity is a familiar sound to UAE people who have experience in desert (safari) camps which are scattered around the country's wasteland. Less familiar is the sight of hybrid energy systems, typically characterized by swirl turbine blades and very large photovoltaic panels. But renewable energy installations are beginning to take root in UAE, characterized with long hours of sunshine throughout the year. These hybrid systems are starting to supplement or even replace diesel generators.

In a hybrid energy system, PV panel is used to provide the primary power source, but because energy from solar irradiation and sunshine is of an intermittent nature, energy must be supplied by other sources during the time that PV has low efficiency. In current systems, diesel generators supply the required electricity for the night activities in the desert camp.

Although a diesel generator may seem relatively inexpensive to purchase, it is expensive to operate and maintain, and it has poor efficiency [1, 2, 3]. Diesel generators emit greenhouse gases, and leaks from fuel storage tanks can contaminate soil and potable water supplies. Changes in landscape of the desert's sand dunes due to diesel generator's operation voice and vibration, is another adverse effect of diesel generators. In addition, isolated safari camps in UAE, like the one shown in figure 1, incur increased diesel fuel costs as a result of long transport distances and are often located in very hostile environments [4].

Fig. 1 Isolated Desert (Safari) Camp in UAE

Hydrogen fuel cell system represents one of the most promising solutions for solving the intermittency in electricity generation that is produced by renewable resources such as solar energy and wind. Recent studies have suggested that a potential solution to provide backup for an unreliable power source, is to use independent renewable energy resources, hence hydrogen fuel cell system. Hybrid energy systems diminish the risk of diesel-related environmental damage and related remediation costs [5]. Despite these environmental benefits, hybrid energy system utilization in remote safari camps is not without challenges. Desert safari activities typically takes place in limited hours and their power needs are proportionately small relative to densely populated community. This creates challenges when attempting to gain cost advantages from economies of scale.

Various combinations of PV panels, diesel generators, batteries, power converters, and fuel cell system were simulated in an effort to find the most cost effective system to satisfy the given electrical load requirements. This study focuses on the feasibility of utilizing a combination of PV-fuel cell system in place of a diesel-battery system to produce energy. Figure 2 presents prototype set up to provide power for a remote areas in UAE.

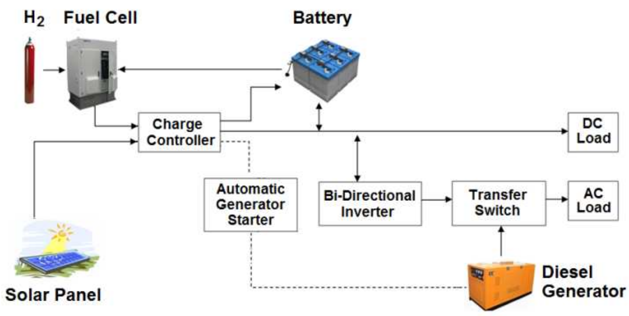


Fig. 2 Experimental Renewable Energy Based System

There are two sections to this study. In the first section, the equivalent circuit parameters of the 3KW fuel cell is performed based on current loading technique and developed model compared to experimental data.

In the second section, the economic feasibility of the renewable energy system shown in figure 2 is investigated. HOMER (computer software simulation tool) was used to conduct the analysis for sizing and optimization. Load requirement variations, capital cost (FC, PV and diesel generator cost) and running cost (Hydrogen, PV cleaning, and diesel cost) has been taken into account at this section.

2. Methodology

A. Experimental Data

Several experiments were conducted on the 3kW ElectraGen^{TM} fuel cell system which is set up in UAE university renewable energy laboratory in Al-Ain, shown in figure 3. The system uses a combination of a Proton Exchange Membrane (PEM) fuel cell and energy storage devices (batteries or capacitors) to provide up to +24 volt uninterrupted DC backup power. The system is connected to a 3 kW load consisting of 30 lamps (100W each) for the experiment purpose and the data was collected using a data acquisition system based on LabView.

Experimentes performed based on current loading technique. In current loading test a no load PEMFC is suddenly turned on to full load (3kW) to obtain the waveform of the transient terminal voltage.

Equivalent circuit model of the fuel cell system is developed based on experimental data. Proposed model has been simulated in PSPICE and results have been compared to experimental values detected via current loading technique.

Figure 3 UAE University Renewable Energy Laboratory

B. Proposed Renewable Energy Based Solution

PV panels are used to provide the primary power source in a hybrid energy system. However, energy from solar irradiation and sunshine is of an intermittent nature, hence energy must be supplied by other sources during the time that PV has low efficiency due to derating factors such as: cloud, high temperature, high dust concentration, shadow, humidity, etc. [6]. In current systems, diesel generators supply the required electricity for the night activities in the desert camp. In the second part of this study, it has been investigated if diesel generator can be replaced by fuel cell system in an efficient way during these periods.

HOMER, a computer model developed by the United States National Renewable Energy Laboratory (NREL), has been used to analyze the feasibility of possible hybrid energy systems. This model incorporates both the physical performance of the system and its lifecycle costs. The life-cycle cost is the total cost of installing and operating the system over its expected life. It includes costs for capital, replacement, operation and maintenance, fuel, and interest.

To obtain the input data utilized by HOMER in modelling the various hybrid systems, data was collected from the following sources: academic and professional journals, written reports, websites, government agencies, various service providers, and personal communication with representatives from component equipment manufacturers.

Critical independent variables (hereinafter referred to as a sensitivity analysis) are proposed to be fuel cell capital cost and hydrogen prices. Each of these variables simulated and tested for within the following specified range: Fuel cell capital cost 100% to 10% and hydrogen prices \$1.9 to \$3.5 per liter. This enables the study to identify the effects that a change in one of these variables has on the feasibility of the overall system.

C. *PEMFC Equivalent Circuit Model and Parameter Estimation*

The circuit which is needed to perform the current loading technique is shown in figure 4. During the current loading test, a no load PEM Fuel Cell is suddenly turned on and the terminal voltage of PEM fuel cell will gradually reach the steady state [7].

The main properties that can be procured using current loading technique are the ohmic resistance obtained from the instantaneous change in terminal voltage and activation loss calculated from the gradual change in terminal voltage to a steady state value.

In fuel cell, the layer of charge on or near the electrode–electrolyte interface is a store of electrical charge and energy, and as such behaves much like an electrical capacitor. If the current changes, it will take some time for this charge and its associated voltage to dissipate (if the current reduces) or to build up (if there is a current increase) [8]. Hence the activation overvoltage does not immediately follow the current in the way that the ohmic voltage drop does. The result is that if the current suddenly changes, the operating voltage shows an immediate change due to the internal resistance, but moves fairly slowly to its final equilibrium value. One way of modeling this is to represent the charge double layer by an electrical capacitor [9] as shown in figure 4.

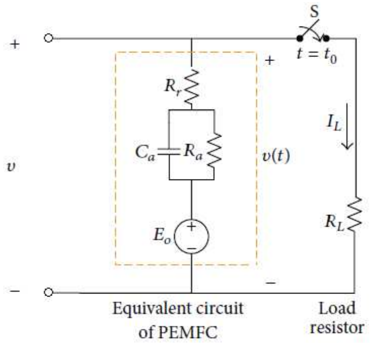


Fig. 4 Circuit for Testing PEMFC under Current Loading Technique

The ohmic losses are represented through the resistor (R_r) which expresses the internal resistance of the PEM Fuel Cell, such as the resistance of electrodes, the resistance of conductive plates, and the resistance of proton which is transferring through the membrane.

The activation losses are represented through the parallel connection of a resistor (R_a) with a capacitor (C_a) that models the double layer of charge at the interfaces between the membrane and the electrodes. The resistor (R_a) models the activation overvoltage and the capacitor 'smoothes' any voltage drop across this resistor. The dc voltage source (E_0) is the theoretical open circuit voltage of the PEMFC.

At time $t = t_0$ the switch S is closed. The terminal voltage corresponding to time $t < t_0$ can be expressed as $v(t < t_0) = E_0$. The terminal voltage corresponding to time $t > t_0$ can be obtained from the following equation:

$$v(t) = \frac{R_L}{R_L+R_a+R_r}\left(1 - e^{-(t-t_0)/\tau}\right)E_0 + \frac{R_L}{R_L+R_r}e^{-(t-t_0)/\tau}E_0 \quad (1)$$

Where τ is the time constant of the test circuit $\tau = C_0(R_aR_L + R_aR_r)/(R_a + R_L + R_r)$. The terminal voltage corresponding to time $t = t_0^+$ where t_0^+ is the time immediately after t_0, is given as follows: $v(t = t_0^+) = \frac{R_L}{R_L+R_r}E_0$. The steady state terminal voltage after the switch is closed can be calculated by $v_{ss} = \frac{R_L}{R_L+R_r+R_a}E_0$. The terminal voltage corresponding to time $t = t_0 + \tau$ can be calculated by:

$$v(t = t_0 + \tau) = \frac{R_L}{R_L+R_a+R_r}(1 - e^{-1})E_0 + \frac{R_L}{R_L+R_r}e^{-1}E_0 \quad (2)$$

The activation losses capacitor C_a can be derived from the time constant $C_a = \frac{R_a+R_r+R_L}{R_a(R_r+R_L)}\tau$

After the equivalent circuit parameters were measured, equivalent circuit model has been simulated in PSPICE and simulated results have been compared to experimental results detected from current loading technique.

D. Modelling the Hybrid Energy System in HOMER

The hybrid system components being considered are as follows: diesel generators, PV panel, fuel cells, hydrogen storage tanks, batteries, and power converters. Research has been conducted to determine the costs (capital, replacement, and operating and maintenance) of each of these components. In addition, the number of units or size of each component was considered to determine what was needed to service the aforementioned electrical load of 66kWh/d with a corresponding peak load of 7 kilowatts. This load is sufficient to be a backup power for small remote desert camp. The research specific schematic inputted into the HOMER simulation software is shown in figure 5.

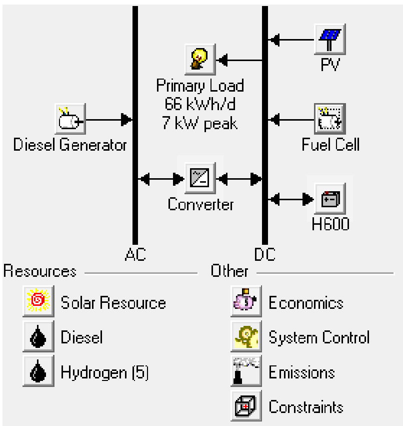


Fig. 5 HOMER Model

It shall be noted that the load requirements at night hours are provided from the combination of Fuel cell and battery pack (figure 2).

Availability of energy from a PV panels is directly rated to the consistency of the solar radiation and is affected by derating factor. A PV solar power measurement system is constructed in the UAEU renewable energy laboratory with geographical location coordinates shown in figure 6.

The SHARP ND-210 PV panels, with a rated capacity of 210 W are installed and chosen to service the electrical load required for small remote desert camp.

The cost of the PV panel was set at $4000 while the replacement costs were considered to be $3500. The operating and maintenance costs were estimated to be $10/yr.

To enable the HOMER simulation software to identify an optimum system the number in the PV search space was inputted at 0 to allow no PV to be chosen as well as at 5, 10, 15, 20 and 25.

Fig 6 PV Installation Site coordinates

The daily electrical load profile of 66kWh/d with a corresponding peak load of 7 kilowatts being used in this study is shown in figure 7.

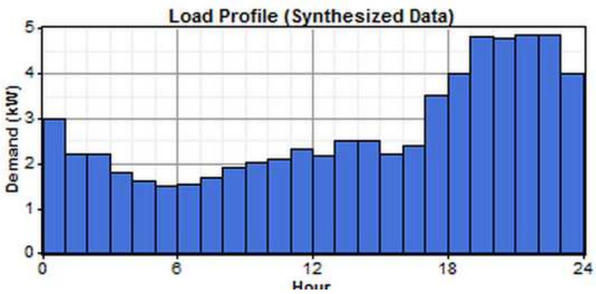


Fig. 7 Daily Load Profile for Desert (Safari) Camp

Table 1 shows the monthly average solar radiation in Al-Ain [10] which has been uploaded into HOMER.

Table 1. Monthly Average Solar Radiation in Al-Ain Camp

Month	Clearness Index	Average Radiation (kWh/m²/day)
Jan	0.545	3.730
Feb	0.593	4.710
Mar	0.561	5.220
Apr	0.617	6.440
May	0.659	7.270
Jun	0.665	7.440
Jul	0.619	6.860
Aug	0.630	6.680
Sep	0.638	6.160
Oct	0.645	5.370
Nov	0.606	4.290
Dec	0.530	3.440

3. Results

A. Circuit Model and Parameter Estimation Results

Using the component models showed in figure 4, a simulation system test bed for the PEM fuel cell system under study has been developed using Pspice. In order to verify the system performance and to validate the proposed circuit model, several simulations have been made and compared.

Simulation studies are carried out for power management during peak load demand in desert camps. The load demand kept the same during simulation.

Experiments were performed based on current loading technique and conducted on the 3kW ElectraGen™ fuel cell system which is set up in UAE university renewable energy laboratory in Al-Ain. The system is connected to a 3 kW load consisting of 30 lamps (100W each) for the experiment purpose as shown in figure 8.

Based on current loading technique, a no load PEMFC is suddenly turned on to full load (3kW) to obtain the waveform of the transient terminal voltage. Data was collected using a data acquisition system based on LabView.

Experiments were conducted on the system in the UAE in the summer at noon and relatively high ambient temperatures ranging from 48°C to 54°C.

Fig. 8 ElectraGen™ fuel cell system and the 3kW load

By applying the equations and equivalent circuit discussed in section 2-C, model for a 3kW ElectraGenTM PEM fuel-cell stack were built in PSPICE environments. A typical current loading testing result is demonstrated below:

$E_0 = 35\ V$, $v(t = t_0^+) = 34\ V$, $v_{ss} = 25\ V$
$R_L = 0.21\ \Omega$, $R_r = 6.186 \times 10^{-3}\ \Omega$, $R_a = 0.0778\ \Omega$
$C_a = 17.449\ F$

Figure 9 shows the experimental values detected from the 3kW ElectraGenTM PEMFC system under current load technique test and PSPICE simulation results.

Note that the experimental results and Pspice model responses agree with each other very well at steady state conditions. The voltage drop at the beginning, shown in figure 9 is due to activation losses.

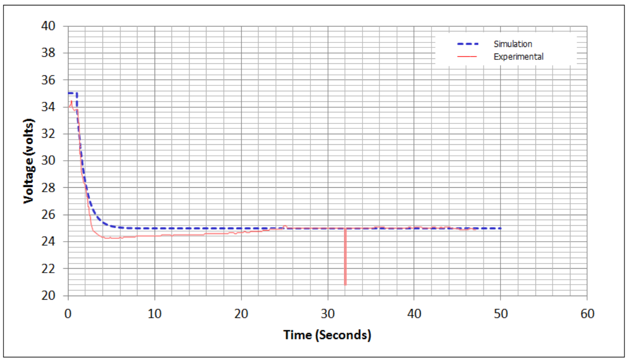


Fig. 9 The simulated and experimental waveform of vStack

This model will be used to further study for the whole experimental set up under different loading conditions.

B. Homer Results

Total net present cost of possible system types at current fuel cell cost is shown in figure 10.

The fuel cell system is not a cost competitive alternative compared to the conventional PV diesel-battery systems.

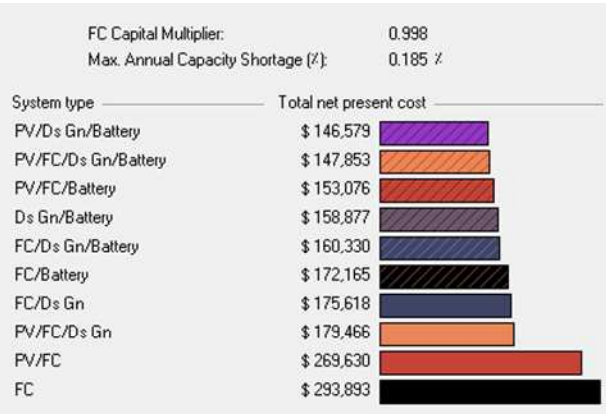


Fig. 10 Total net present cost of possible system types at current FC cell cost

However, with a reduction in fuel cell systems to about 50% of their current costs these systems begin to become cost effective when coupled with a PV-diesel system or being used as independent back-up generator along with batteries (Figure 11).

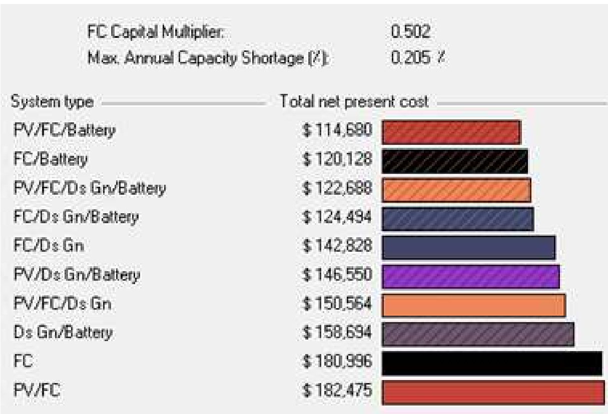


Fig. 11 Total net present cost of possible system types with FC capital cost equal to half of current cost

In figure 12, the sensitivity of solar radiation in m/s was plotted against diesel prices in \$/litre. The third sensitivity variable, fuel cell system capital cost multiplier (faction of capital cost), was fixed at 1.

This model indicated that at current fuel cell system cost (FC capital multiplier fixed at 1) the most economically feasible solution for Solar radiation ranging from 3.5 to 6 kWh/m2/d and diesel prices ranging from \$0.4 to \$1.0/litre is a diesel-battery system.

Considering the fuel cell system costs at present cost, diesel prices to be \$.85/litre, and the average solar radiation to be 5kW/m2/d the net present cost of the system, capital cost, and the cost of energy was found to be \$146,843, \$49,920 and \$.474/kWh respectively.

In figure 13 the diesel cost was plotted against the fuel cell capital cost multiplier (faction of fuel cell system capital cost). The third sensitivity variable, solar radiation was fixed at 4.99kWh/m2. This model more clearly indicates that when the average solar radiation exceeds 4.99kWh/m2 and the fuel cell systems reach 30% of their current capital costs it was economically feasible to meet the electrical load without the diesel generator component. Furthermore, this model revealed that this result was almost absolutely independent of the price of diesel within the range of \$.4 to \$1.0/litre. Considering the fuel cell system capital costs to be 30% of present costs, diesel prices to be \$.85/litre, and the average solar radiation to be 4.99kWh/m2, the net present cost of the system, capital cost, and the cost of energy (COE) was found to be \$95,911, \$37,170, and \$.310/kW respectively.

However, with a reduction in fuel cell systems to about 50% of their current costs these systems begin to become cost effective when coupled with a PV-diesel system or being used as independent back-up generator along with batteries.

Figure 14 shows that with the Solar radiation fixed at 4.99kWh/m2, the diesel price fixed at \$.85/litre, and the fuel cell system capital multiplier fixed at 1 (current cost) the most economically feasible system configuration is 5kW PV panel, 5kW diesel generator, 64 H600 batteries and a 5kW power converter.

The net present cost of this system, annual operating costs, and annual cost of energy are \$146,843, \$7,582, and \$.474/kWh. These numbers are specifically targeted as they represent UAE's current average solar radiation, diesel price, and fuel cell system costs respectively with the solar radiation fixed at 4.99kWh/m2, the diesel price fixed at \$.85/litre, and the fuel cell system capital multiplier fixed at 0.4 of current costs.

The optimum system configuration in this scenario has replaced the diesel generator with fuel cell system and PV. The net present cost of this system, annual operating costs, and annual cost of energy were \$106,487, \$5,548 , and \$.344/kWh.

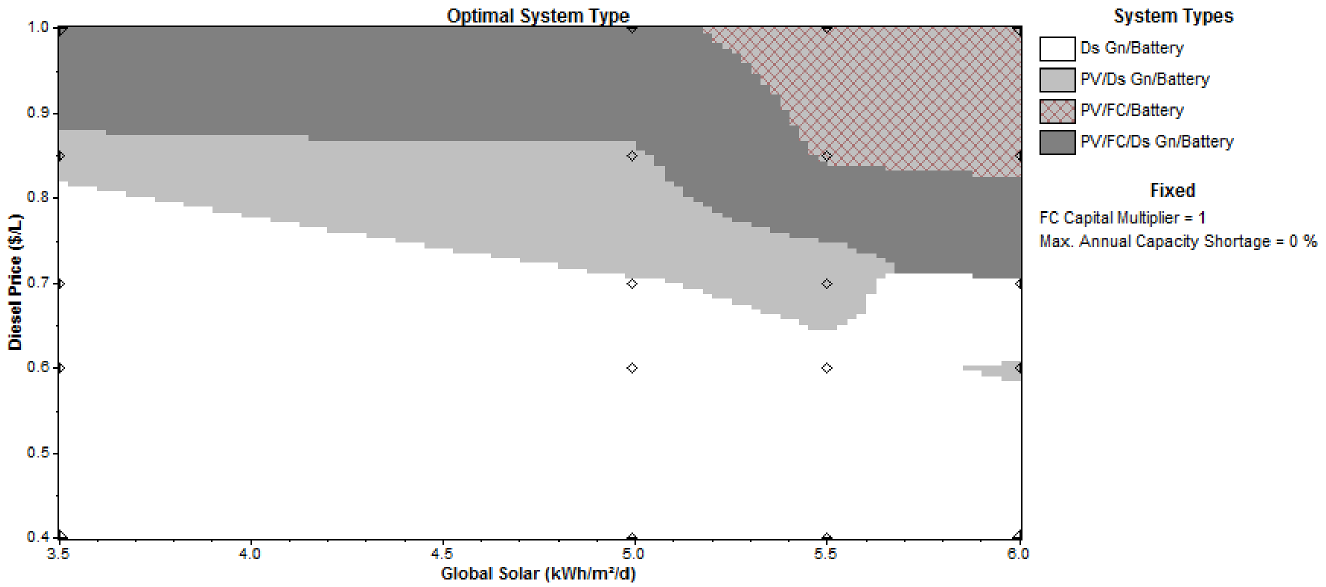


Fig 12 Diesel Price versus Solar Radiation with FC Multiplier at 1

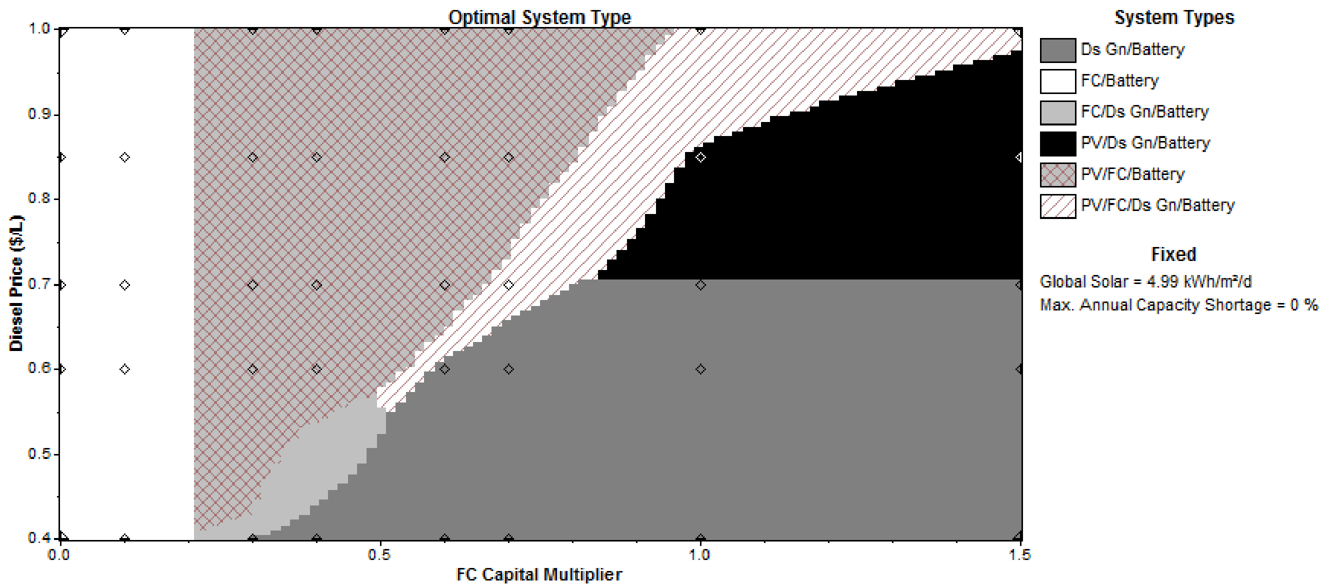
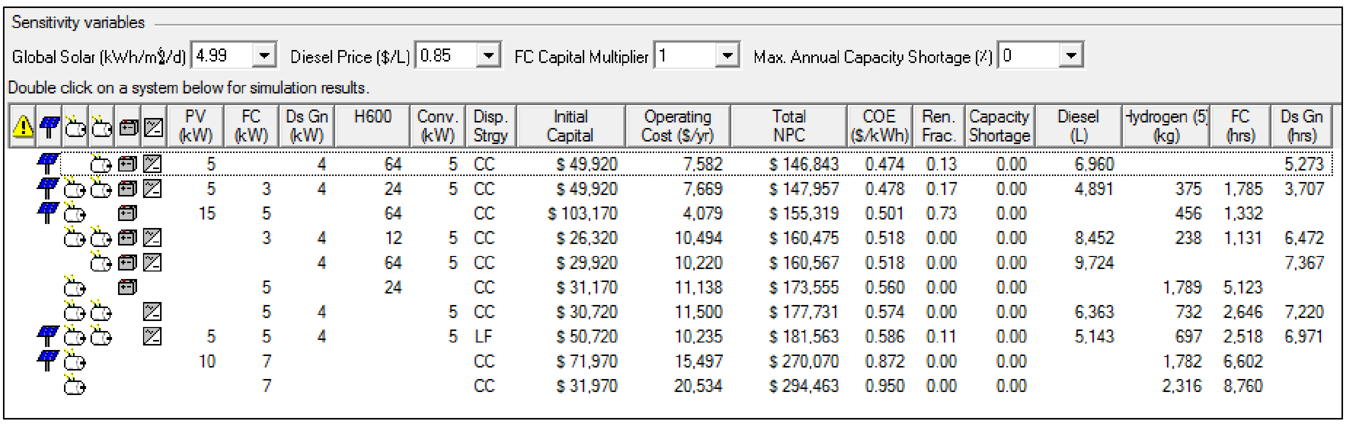


Fig 13 Diesel versus FC Costs with Solar Radiation at $4.99 kWh/m^2$



Sensitivity variables

Global Solar (kWh/m²/d) 4.99 Diesel Price ($/L) 0.85 FC Capital Multiplier 1 Max. Annual Capacity Shortage (%) 0

Double click on a system below for simulation results.

PV (kW)	FC (kW)	Ds Gn (kW)	H600	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Hydrogen (5) (kg)	FC (hrs)	Ds Gn (hrs)
5		4	64	5	CC	$ 49,920	7,582	$ 146,843	0.474	0.13	0.00	6,960			5,273
5	3	4	24	5	CC	$ 49,920	7,669	$ 147,957	0.478	0.17	0.00	4,891	375	1,785	3,707
15	5		64		CC	$ 103,170	4,079	$ 155,319	0.501	0.73	0.00		456	1,332	
	3	4	12	5	CC	$ 26,320	10,494	$ 160,475	0.518	0.00	0.00	8,452	238	1,131	6,472
		4	64	5	CC	$ 29,920	10,220	$ 160,567	0.518	0.00	0.00	9,724			7,367
	5		24		CC	$ 31,170	11,138	$ 173,555	0.560	0.00	0.00		1,789	5,123	
	5	4		5	CC	$ 30,720	11,500	$ 177,731	0.574	0.00	0.00	6,363	732	2,646	7,220
5	5	4		5	LF	$ 50,720	10,235	$ 181,563	0.586	0.11	0.00	5,143	697	2,518	6,971
10	7				CC	$ 71,970	15,497	$ 270,070	0.872	0.00	0.00		1,782	6,602	
	7				CC	$ 31,970	20,534	$ 294,463	0.950	0.00	0.00		2,316	8,760	

Fig 14 Optimization Results with Solar, Diesel, and FC Capital Multiplier Fixed at (4.99, 0.85, 1)

4. Conclusion

Homer model analyzes the options for providing power to remote desert camp. The three possible sources of power are photovoltaic, Hydrogen fuel cell and Diesel generator. The possible storage media is battery bank.

Sensitivity has been performed on the cost of the hydrogen subsystem. The optional system type graph in figure 13, shows that the hydrogen subsystem must come a long way down in price for it to be competitive with diesel generator. Moreover most of the cases when HOMER does recommend the hydrogen system, it also recommends the battery bank. Only in one corner of the sensitivity space where the hydrogen fuel cell system and hydrogen tank are virtually free, does HOMER recommend the hydrogen system unaccompanied by a battery bank.

Remote location of the camps and difficulty of delivering diesel and hydrogen tanks is another point that should take into consideration. Pointing out that in most of the cases, especially during the day time when the PV panels are able to generate maximum power and consumption is min, system produces more power than what is required for load at a given time. This extra generated power can be coupled with electrolyzer and used to generate and store hydrogen for the fuel cell operation during the night. Considering that water electrolysis technology has the highest energy efficiency in non-fossil fuel based hydrogen production, it is ideally suited for coupling with PV field in order to use the surplus generated renewable power to produce and store hydrogen at high efficiency.

The stored hydrogen in storage tank can be consumed when required by the fuel cell. Such a standalone PV-Hydrogen Fuel Cell System, diminish the risk of diesel-related environmental damage and will reduce difficulties and extra effort for supplying the Hydrogen source to the middle of desert.

Despite these environmental benefits, hybrid energy system utilization in remote safari camps is not without challenges in addition to extra capital, maintenance and operation costs of the hydrogen producer and Hydrogen storage system.

An electrical equivalent circuit of the fuel cell has been developed. The electrical circuit elements has been calculated and estimated based on current loading test and experimental results collected from ElectraGenTM fuel cell under study. The model was used in the simulation of the fuel cell. Simulation results revealed that the model matches experimental data very well at steady state conditions. The model will be used to further study the whole experimental set up under different loading conditions.

Acknowledgement

This research work is sponsored by the United Arab Emirates University (UAEU) in Al Ain – UAE.

References

[1] C.V Nayar, S.J. Phillips, W. L. James, T.L. Pryor, and D.Remmer, "Novel Wind/Diesel/Battery Hybrid Energy System".Elsevier Solar Energy Vol. 51, no 1, pp. 65-78, July 1993.

[2] E. Akyuz and Z. Oktay,"The techno-economic andenvironmental as pects of a hybrid PV-diesel-battery power system for remote farm houses", Int. J. Global Warming, Vol. 1, pp. 392-404, 2009.

[3] K. Qian, P.S. Solanki, V.S. Mallela, M. Allan, and C. Zhou, "A Hybrid Power System Using Wind and DieselGenerator: A case Study at Masirah Island In Oman", 20thInternational Conference on Electricity Distribution", Prague, 8-11 June 2009.

[4] O. Zoubeidi, A.A. Fardoun, H. Noura and C. Nayar, "'Hybrid Renewable Energy Solution for Safari Camps", IEEE International Energy conference and Exhibition (EnergyCon), pp 244-249, December, 2010.

[5] G. Mahar and G. Simmons, "Feasibility of Utilizing Hydrogen Fuel Cell Systems in Hybrid Energy Systems, In Stand-Alone Off-Grid Remote Northern Communities of Canada" Feb 2011

[6] B. Raton: Taylor & Francis Group. Patel, Wind and Solar Power Systems: Design, Analysis, and Operation. 2nd Ed. M.R., (2006)

[7] W. Y. Chang, "Application of current switching method to estimate the model parameters of proton exchange membrane fuel cell," mulation Modelling Practice and Theory, vol. 18, no. 1, pp. 35–50, 2010.

[8] J. Larminie and A. Dicks, Fuel Cell Systems Explained, John Wiley & Sons, Landon, UK, 2nd edition, 2003.

[9] W. Yeau Chan, Equivalent Circuit Parameters Estimation for PEM Fuel Cell Using RBF Neural Network and Enhanced Particle Swarm Optimization, St. John's University, December 2012;

[10] Surface meteorology and Solar Energy, A renewable energy resource web site (release 6.0), sponsored by NASA's Earth Science Enterprise Program, Available Online: https://eosweb.larc.nasa.gov/sse/RETScreen/