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DESIGN AND SIMULATION OF A HYBRID PV/FUEL CELL ENERGY SYSTEM

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ABSTRACT
This paper shows the way to design the aspects of a hybrid power system that will target remote users. The main power for the hybrid system comes from the photovoltaic (PV) panels, while the fuel cell (FC) and secondary batteries are used as backup units. Converter is incorporated, since the system will feed an AC load which is not connected to the grid. During the day, the PV array produces much more power than needed by the load, with the surplus going to the electrolyzer and the battery. At night the FC will serve the load while drawing hydrogen from the storage tank. In this system, the hydrogen tank starts the year full and ends it empty. The optimization software used for this work is the Hybrid Optimization Model for Electric Renewable (HOMER). HOMER is a design model that determines the optimal architecture and control strategy of the hybrid system. A sensitivity analysis reveals how sensitive the outputs are to changes in the inputs. In this system we specified one sensitivity variable with two values; which are the slope of fuel consumption in FC and the marginal fuel consumption of the FC. It shows that the Net Present Cost (NPC) and the Cost of Energy (COE) have increased due to the rise in fuel consumption in the FC from 0.03 to 0.05 L/hr/Kw.

KEYWORDS: Hybrid; Photovoltaic; Fuel cell; Stand-alone.

INTRODUCTION

Renewable energy sources (solar, wind, etc) are attracting more attention as alternative energy sources than conventional fossil fuel energy sources. This is not only due to the diminishing fuel sources, but also due to environmental pollution and global warming problems. Among these sources is the solar energy, which is the most promising, as the fabrication of less costly photovoltaic (PV) devices becomes a reality. With increased penetration of solar PV devices, various antipollution apparatus can be operated such as water purification through electrochemical processing and stopping desert expansion by PV water pumping with tree plantation However, control problems arise due to large variances of PV output power under different insolation levels. To overcome this problem, PV power plants are integrated with other power sources or storage system such as hydrogen generator, storage and fuel cells (FC) [1-2].

Commonly hybrid energy systems use solar, wind, and hydro energy sources, although most of the renewable energy available on earth consists of different forms of solar energy. A system of the combination of these different sources has the advantage of being balance and stability [3].

Solar energy is one of the in-exhaustible energy sources available for the implementation of renewable energy system in remote areas. It has been pursued by a number of countries with monthly average daily solar radiation in the range of 3-6 kWh/m^2 in an effort to reduce their dependence on fossil fuels [4]. Malaysia, being gifted with abundance of solar radiation, has a wide potential of solar energy applications to meet the electricity demand of remote villages [5].

A. Photovoltaic-Electrolyzer-Fuel Cell System:

For many applications, a loss of feeding loads is not acceptable. In order to achieve no loss of feeding load probabilities with a PV generator, the system must be designed according to the worst case climate and load conditions. Therefore, another source of energy is necessary to realize energy storage. In this system, the excess energy is stored in the form of compressed hydrogen via conversion through the electrolyzer. The fuel cell is used to produce power if the load power exceeds that produced from the PV generator. It can also function as an emergency generator, if the PV generator system fails. With a total efficiency of the storage system in the range of 50%, a suitable storage volume can be achieved and the PV generator capacity can be reduced significantly. This compensates partially the extra cost of the hydrogen system. Based on the site climate, the load profile, the characteristic of the components and the storage volume can be optimized [6],[7]. And for many years, a number of hybrid systems have been realized using hydrogen for seasonal energy storage. Different system topologies have been used. Most common is the DC/AC connection of PV generator, electrolyzer, and fuel cell with, or even without, a DC/DC converter. All these system topologies will be studied in details in this work. Technically, this system can store not only the hydrogen but also the oxygen. But, due to safety problems and extra costs, oxygen storage is not used and the fuel cell can be operated with the oxygen from air.

B. HOMER Software:

Hybrid Optimization Model for Electric Renewable (HOMER) Software performs comparative economic analyses on a distributed generation power systems. Inputs to HOMER will perform an hourly simulation of every possible combination of components entered and rank the systems according to user-specified criteria, such as cost of energy (COE) or capital costs. Furthermore, HOMER can perform “sensitivity analyses” in which the values of certain parameters (e.g., fuel cell cost) are varied to determine their impact on the COE. To obtain the input data for HOMER, hydrogen component information is collected from research literature and manufacturers. This data will be used by HOMER can to estimate the present and future of hydrogen system costs and efficiencies [8].

I. SYSTEM DESCRIPTION

The Hybrid system is made up of a renewable energy generator (PV), an inverter (DC/AC converter), a back-up unit fuel cell (FC) and a storage system (batteries).

A. PV System

Figure 1 shows the current output of a PV panel as a function of voltage and as a function of solar radiation. As solar radiation (insolation) increases, so do both the current and the voltage of the panel. The panel’s power output can be found by multiplying the current and the voltage. The black points on the diagram denote the point at which the maximum power is collected from the panel. If a Maximum Power Point tracker is included in the PV system, the load on the panel is adjusted so that the panel always outputs its maximum power.

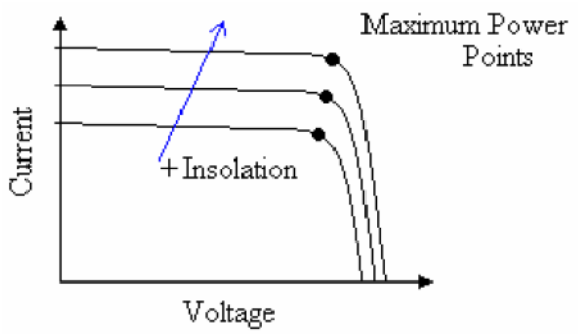


Figure 1: I-V Characteristic of PV Array [2]

The simulated array has a rated efficiency of 12%. The rated (peak) power of the array, as well as the slope and azimuth can be adjusted. The peak power is obtained under 1000 W/m² for a cell temperature of 25°C. The PV array is assumed to be equipped with a Maximum Power Point Tracker (MPPT) which optimizes its power output [3].

Array slope angle describes the angle at which the photovoltaic modules are tilted. Often modules are tilted to an angle equal to the location’s latitude. In order to maximize summer energy collection, modules should be tilted less (they should be more horizontal). In order to maximize winter energy collection, they should be more vertical [9]. A slope of 0^o indicates that the modules are horizontal and the slope of 90^o means that they are vertical [9].

Array azimuth angle describes the direction that the photovoltaic array modules face. Due south is defined as an azimuth of 0^o. Angles that are east of due south are defined as negative azimuths and angles that face west of due south are defined as positive azimuths. For instance an Array facing due west has an azimuth angle of 90 degrees, while an array facing South-East has an azimuth angle of -45 degrees [9].

B. Electrolyzers

Proton exchange membrane (PEM) electrolyzers from Proton Energy Inc. were used to obtain a cost estimate of a stand-alone ("hydrogen by wire") electrolyzer. The system used to obtain a $/kW cost for electrolyzers include the PEM stack, power electronics, and control system. Cost reductions are expected to stem from improvements in the PEM stack, power electronics, control system, and manufacturing improvements such as replacing fittings with welded tube assemblies. These costs assume production of 500 units per year [10].

Conventional electrolyzers produce hydrogen at low pressure (100-200 psi). Compressors are used to elevate the pressure for gas storage. However, 2,500-3,000psi production pressures have been demonstrated recently at Proton energy and are expected to be in production in the very near future; targets are upward of 6,000 psi. Such technologies will likely eliminate the need for compressors. Accordingly, this study assumed that a compressor was not required [10].

C. Fuel Cells

The fuel cell (FC) is an electrochemical device that produces direct current electricity through the reaction of hydrogen and oxygen in the presence of an electrolyte. They are an attractive option for use with intermittent sources of generation, like the PV, because of high efficiency, fast load response, modularity, and fuel flexibility. Unlike a battery, a FC does not require recharging. Their feasibility in coordination with PV systems has been successfully demonstrated for both grid-connected and stand alone applications [1].

Other advantages of FC are the reusability of exhaust heat, on-site installation, and diversity of fuels. The fuel for the FC can be hydrogen or any other hydrogen-containing compound, which on reprocessing can produce hydrogen. The use of electrolysis to produce hydrogen from water is an efficient method for very small to very large scales. Additionally, when PV is used with the electrolyzer, it is the cleanest source of hydrogen with no pollutants produced. On the small scale, a PV array coupled to an electrolyzer and hydrogen (H_2) storage tank provides a flexible system, which could be installed in any location with just a little maintenance [1].

A PEM fuel cell is considered in this study. The cost of fuel cells varies widely depending on scale, power electronics requirements, and reformer requirements. A survey performed for this study identified PEM fuel cell that currently sell for between $3,000/kW to 6,000/kW [11].

The I-U and I-P characteristics of a PEM fuel cell are presented in Fig. 2. They can be divided into three regions, which are governed by different over-voltages. Activation over-voltage dominates at low current densities in region I. Region II is governed by the ohmic losses and in region III bending down of the polarization curves due to the concentration over-voltage. Some fuel cells are not operated at high enough currents to ever see the effects of losses in region III. Hydrogen and oxygen pressures in a H_2/O_2 PEM fuel cell during operation are kept fairly constant. In an H_2/Air PEM fuel cell, a fan is usually used to force atmospheric air across the cathode side. The overall performance of the PEM fuel cell can be improved by increasing one or all of the following conditions: (1) temperature of the PEM fuel cell (20-80°C); (2) hydrogen and/or oxygen pressure (1-5 Bar); (3) flow rates of hydrogen and oxygen [6].

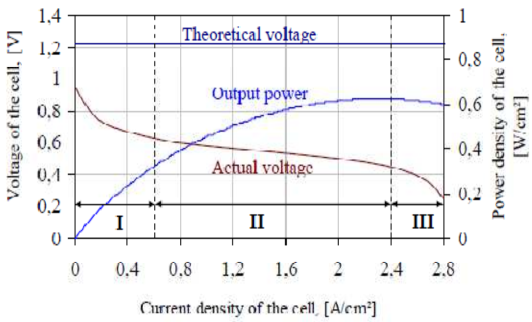


Figure 2: Characteristic curves of a PEM FC [4]

Stationary fuel cells are targeted to last 30,000 to 40,000 hours, during which the membrane will likely have to be replaced one or more times. This study assumed the fuel cell would last for 30,000 hours. The efficiencies of PEM fuel cells running on pure hydrogen are roughly 40% to 50% (lower heating value) at rated power with slightly higher values at partial load. The electrical efficiency used for this study is held constant at 45% to compensate for parasitic losses, which occur at partial load [10].

D. Inverter

The inverter was rated based on the selected PV array. Since 3.3 kW output would be generated from PV, the inverter was rated up to 5.0 kW to fully supply the power from PV. However, it is assumed that the inverter has an efficiency of 90%. Therefore, the supplied power would be less than 5 kW. The initial cost of the inverter is assumed to be 716 $/kw, while the replacement cost is 700 $/kw. There was operating and maintenance cost estimated as 40 $/kw/yr.

E. Battery Bank

The battery bank is a collection of one or more individual batteries. HOMER models, a single battery as a device capable of storing a certain amount of DC electricity at fixed round-trip energy efficiency, with limits as to how quickly it can be charged or discharged, how deeply it can be discharged without causing damage, and how much energy can cycle through it before it needs replacement. HOMER assumes that the properties of the batteries remain constant throughout its lifetime and are not affected by external factors such as temperature [12].

In HOMER, the key physical properties of the battery are its nominal voltage, capacity curve, lifetime curve, minimum state of charge, and round-trip efficiency. The capacity curve shows the discharge capacity of the battery in ampere-hours versus the discharge current in amperes. Manufacturers determine each point on this curve by measuring the ampere-hours that can be discharged at a constant current out of a fully charged battery. Capacity typically decreases with increasing discharge current. The lifetime curve shows the number of discharge–charge cycles the battery can withstand versus the cycle depth. The number of cycles to failure typically decreases with increasing cycle depth. The minimum state of charge is the state of charge below which the battery must not be discharged to avoid permanent damage. In the system simulation, HOMER does not allow the battery to be discharged any deeper than this limit. The round-trip efficiency indicates the percentage of the energy going into the battery that can be drawn back out [12].

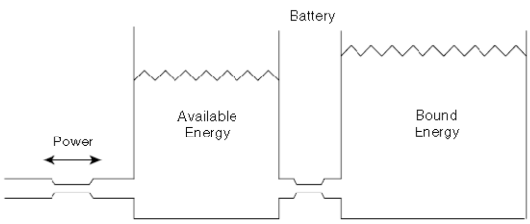


Figure 3: Kinetic battery model concepts

Depth of discharge is a measure of how much energy has been taken from a battery. With the lead-acid deep cycle battery used in a solar electric system, there is more tolerance for discharging. You can discharge the battery of a solar energy system 50% to 80% with no damage to the battery. This makes it very different from a car battery, (also called a *start battery*) [12].

SYSTEM MODELING AND SIMULATION

HOMER can simulate a wide variety of hybrid system configurations, comprising any combination of a PV array, one or more wind turbines, a run-of-river hydro turbine, and up to three generators, a battery bank, an AC - DC converter, an electrolyzer, and hydrogen storage tank. The system can be grid-connected or autonomous and can serve AC and DC electric loads and a thermal load.

Figures (4, 5, and 6) show schematic diagrams of some examples of the types of hybrid systems that HOMER can simulate.

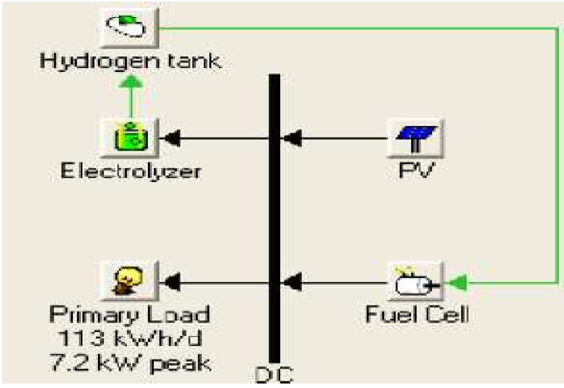


Figure 4: PV– electrolyzer - hydrogen tank - fuel cell

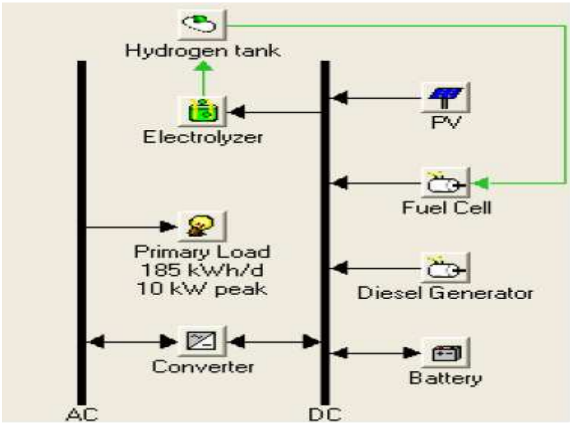


Figure 5: PV-fuel cell–diesels - battery and ac–dc converter

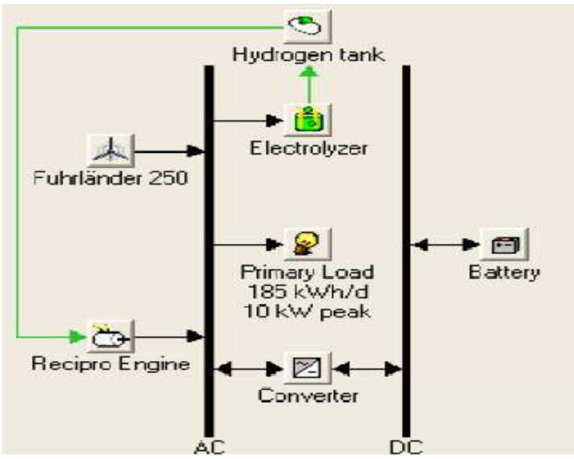


Figure 6: A wind-powered system using both batteries and hydrogen for backup

In Figure 4 a PV–hydrogen system in which an electrolyzer converts excess PV power into hydrogen, with a hydrogen tank stores for use in a fuel cell during times of insufficient PV power. Figure 5 a PV-fuel cell–diesel system with battery backup and an ac–dc converter, and Figure 6 a wind-powered system using both batteries and hydrogen for backup, where the hydrogen fuels an internal reciprocating engine generator. The simulation process serves two purposes. It determines whether the system is feasible, and estimates the life-cycle cost of the system; which is the total cost of installing and operating the system over its lifetime. HOMER considers the system to be feasible if it can adequately serve the electric and thermal loads and satisfies any other constraints imposed by the user. The life-cycle cost is a convenient metric for comparing the economics of various system configurations [8].

A. System Design

For this design work, the photovoltaic module has been used as the main source of power generation. A battery bank is employed to store energy. A fuel-cell stack is used as a back-up source. The photovoltaic module with the battery and the electrolyzer are connected to the load through the dc/ac converter as shown in figure 7. During operation, the fuel cell is also connected directly with the load. The idea of this system is to operate the load with photovoltaic electricity and use the battery bank during high insolation periods. The electrolyzer produces H_2 from the excess photovoltaic energy during the day; which is stored for the time being and the fuel cell converts the H_2 back to electricity during the time of low insolation. The battery storage system is used for short-term storage of electricity and to supply power to load.

The system specified the FC generator schedule (operation mode) as forced on from 7-pm to 8-am. Since the PV will not produce at the night. During that time the FC generator is adjusted as optimized source to either force on or off, HOMER decides whether it should operate based on the needs of the system and the relative costs of the other power sources. For the generator force on, HOMER decides at what power output level it will operate, which may be anywhere between its minimum and maximum power output.

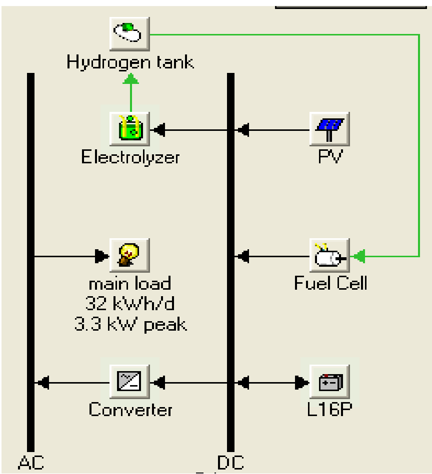


Figure 7: The system design

B. System Optimization

The aim of the optimization process is to find the optimal value of each decision variable that interests the modeler. Possible decision variables in the system include:

- The size of PV array.
- The size of fuel cell generator.
- The size of the converter.
- The number of batteries.
- The size of the electrolyzer.
- The size of the hydrogen storage tank.

Usually, batteries are used to store energy for a short period of term (efficiency 70%) and hydrogen allows the energy storage over the seasons. The total efficiency is about 40% (electrolyzer 80% + gases storage 10% + fuel cell 50%).

In the optimization process, HOMER simulates every system configuration in the search space and displays the results in a table, sorted by total net present cost. In the overall list shown in table 1, the top ranked system is the least cost configuration within the PV-FC-battery system category. The first row in table 1 is the optimal system configuration, meaning that, the one with the lowest net present cost. In this case, the optimal configuration contains PV- 21 kW, the 4-KW FC generator, no batteries, 4 Kw of converter, 9 Kw of electrolyzer, and a 27 kg of H_2 tank. The second-ranked system is the same as the first except that it has different dispatch strategy which is load following (LF) as against of cycle charging (CC). For this system the power flow data in some days in January is given in figure 8. The yellow curve is the power from PV, and the black curve is the power from FC. The load power is changing as shown by the blue curve. The daily load profile of an AC load is as shown in figure 9. It can be noticed that load requirement varies throughout the day, with the maximum demand occurs at afternoon and evening. However, at noon, electricity customers would be at home for lunch and rest, which caused the load demand to increase. Load requirements further changes according to each month. This is shown in figure 10. It was assumed that the hottest month occurs on August. Therefore, the load requirements would be a little higher for this month. However, it was assumed that almost all the months would require same electricity demand.

At the end of the year the hydrogen storage will be zero. The categorized optimization results list shown in Table 2 makes it easier to see the least-cost configuration for each category by eliminating the need to scroll through the long list of systems displayed in the overall list.

C. System Sensitivity Analysis

In a sensitivity analysis, a variable for which the user has entered multiple values is called a sensitivity variable. Almost every numerical input variable in HOMER which is not a decision variable can be a sensitivity variable. Examples include the fuel price, intercept coefficient, the interest rate, or the lifetime of the PV array.

HOMER performs a separate optimization process for each sensitivity case and presents the results in various tabular and graphic formats.

Table 1 Optimization results table showing system configurations sorted by total net present cost

PV (kW)	FC (kW)	L16P	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	FC (hrs)	Batt. Lf. (yr)
21	4		4	9	27	CC	$ 136,594	4,602	$ 195,424	1.330	1.00	0.00	5,905	
21	4		4	9	27	LF	$ 136,594	4,602	$ 195,424	1.330	1.00	0.00	5,905	
21	4		5	9	27	CC	$ 137,310	4,661	$ 196,889	1.340	1.00	0.00	5,905	
21	4		5	9	27	LF	$ 137,310	4,661	$ 196,889	1.340	1.00	0.00	5,905	
21	6		4	9	27	CC	$ 137,394	4,980	$ 201,052	1.368	1.00	0.00	5,905	
21	6		4	9	27	LF	$ 137,394	4,980	$ 201,052	1.368	1.00	0.00	5,905	
21	6		5	9	27	CC	$ 138,110	5,038	$ 202,517	1.378	1.00	0.00	5,905	
21	6		5	9	27	LF	$ 138,110	5,038	$ 202,517	1.378	1.00	0.00	5,905	
21	4		4	9	35	CC	$ 143,794	4,642	$ 203,135	1.382	1.00	0.00	5,905	
21	4		4	9	35	LF	$ 143,794	4,642	$ 203,135	1.382	1.00	0.00	5,905	
21	4		5	9	35	CC	$ 144,510	4,701	$ 204,600	1.392	1.00	0.00	5,905	
21	4		5	9	35	LF	$ 144,510	4,701	$ 204,600	1.392	1.00	0.00	5,905	
25	4		4	9	15	CC	$ 142,714	4,872	$ 204,992	1.395	1.00	0.00	5,728	
25	4		4	9	15	LF	$ 142,714	4,872	$ 204,992	1.395	1.00	0.00	5,728	
25	4		5	9	15	CC	$ 143,430	4,930	$ 206,457	1.405	1.00	0.00	5,728	
25	4		5	9	15	LF	$ 143,430	4,930	$ 206,457	1.405	1.00	0.00	5,728	
21	6		4	9	35	CC	$ 144,594	5,020	$ 208,764	1.420	1.00	0.00	5,905	
21	6		4	9	35	LF	$ 144,594	5,020	$ 208,764	1.420	1.00	0.00	5,905	
21	6		5	9	35	CC	$ 145,310	5,078	$ 210,229	1.430	1.00	0.00	5,905	
21	6		5	9	35	LF	$ 145,310	5,078	$ 210,229	1.430	1.00	0.00	5,905	

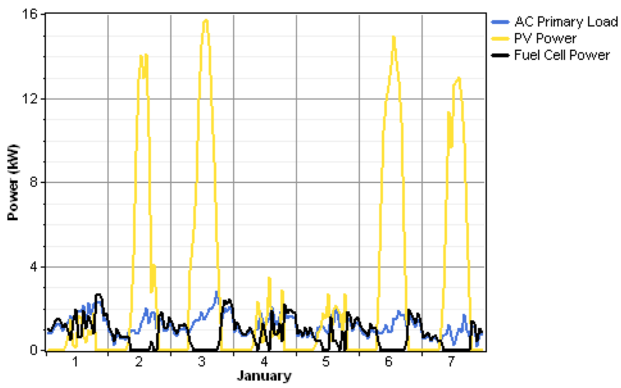


Figure 8 Hour data power flow in days from January

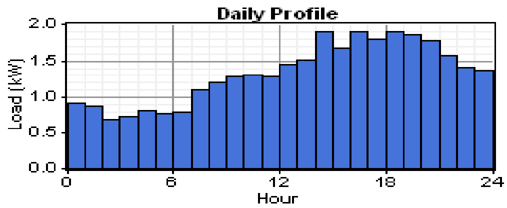


Figure 9 Daily load profile.

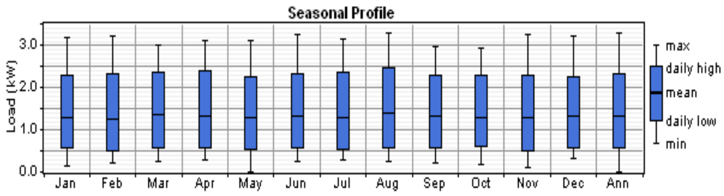


Figure 10 Monthly load profiles.

CONCLUSION

This design work investigates the modeling of a stand-alone power system using PV and fuel cell as a source. Inverter is used, since the system was designed to feed an AC load not connected to grid. During the day, the PV array produces much more power than needed by the load, which the surplus is routed to the electrolyzer and the battery. At the night the FC serves the load. The battery is incorporated to serve during emergency cases (for short time) and to assist the FC during transient periods.

A sensitivity analysis reveals how sensitive the outputs are to changes in the inputs. In this system one sensitivity variable with 2 values has been specified; the slope of fuel consumption in the FC and the marginal fuel consumption of the FC. It can be seen from table 3 that the operating cost, the total NPC, and the cost of energy
(COE) have increased due to the rise in fuel consumption in the FC from 0.03 to 0.05 L/hr/kW.

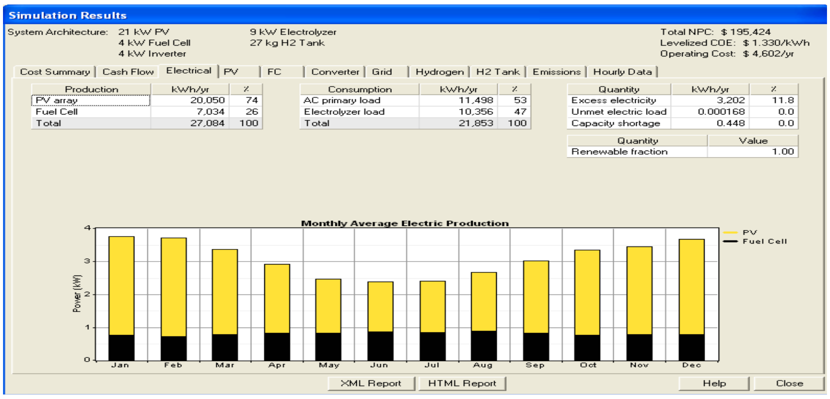
HOMER only considers the economical aspects, and so the capacity of fuel cell is small compared to PV. This is because the cost for the FC is a little expensive as compared to PV.

Table 2 Categorized optimization results table

	PV (kW)	FC (kW)	L16P	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	FC (hrs)	Batt. Lf. (yr)
	21	4		4	9	27	CC	$ 136,594	4,602	$ 195,424	1.330	1.00	0.00	5,905	
	21	2	48	4	9	27	CC	$ 157,394	5,715	$ 230,450	1.568	1.00	0.00	5,485	10.0
	21		224	4			CC	$ 199,494	10,629	$ 335,368	2.282	1.00	0.00		10.0

Table 3 Sensitivity cases of the system configuration based on two values of the slope of fuel consumption in FC

FC FC Slope (L/hr/kW)		PV (kW)	FC (kW)	L16P	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	FC (hrs)	Batt. Lf. (yr)
0.030		21	4		4	9	27	CC	$ 136,594	4,602	$ 195,424	1.330	1.00	0.00	5,905	
0.050		25	2	48	4	9	15	CC	$ 163,514	7,542	$ 259,924	2.193	1.00	0.00	8	9.2



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