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Pre-Feasibility Study of Hybrid Hydrogen Based Energy Systems for Coastal Residential Applications

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Abstract: Problem statement: The purpose of this study is to design a renewable energy hydrogen based power system to provide electricity to a coastal residential area in east coast area (Kuala Terengganu) of Malaysia. **Approach:** The selected case study represents a power demand of 20 kWh day^{-1}. The autonomous system used in this study is diesel generator, wind and photovoltaic hybrid system. The power system was redesigned and optimized as hydrogen-based autonomous power systems in order to meet the existing user's power demand at a minimum cost of energy. Wind speed and solar radiations data obtained from Malaysian Meteorological Department have been used in the simulation process through optimization software, Hybrid Optimization Model for Electric Renewables (HOMER). **Results:** Three systems that were considered in this study area are stand alone PV-wind-diesel, stand alone PV-wind-hydrogen and grid connected PV-wind-hydrogen energy system. The proposed systems then were compared regarding on their operational characteristics and cost values. The comparisons prove that grid connected PV-wind-hydrogen energy system had the lowest total net present cost and cost of energy, $53,197 and $0.57/kWh, respectively that makes it the most cost effective system and followed by PV-wind-diesel and stand alone PV-wind-hydrogen system. **Conclusion/Recommendations:** It can be concluded that the hydrogen-based system can become a favorable system without aid from the grid system and bring advantage in technical and economic point of view and also suitable to be applied in the coastal residential application as energy carrier if only the current cost of wind turbine, PV arrays and hydrogen system technology have been reduced to its minimum rate.

Key words: Cost of energy, HOMER, Hydrogen based power system, Kuala Terengganu, net present cost

INTRODUCTION

At present, renewable energy based low-emission hybrid energy systems with hydrogen storage are not cost-competitive against conventional fossil fuel based stand-alone or grid interfaced power systems. However, the need for cleaner power and improvements in alternative energy technologies bear good potential for widespread use of such systems (Khan and Iqbal, 2005). Various energy sources (wind, solar, diesel generator) and storage systems (battery, electrolyzer-hydrogen tank) were normally considered in such analysis. In these studies the National Renewable Energy Laboratory's (NREL) optimization tool "HOMER" was used in identifying probable hybrid configurations and their applicability.

Zoulias and Lymberopoulos (2007) examine the techno-economic aspects of replacing diesel generators and batteries of the system by hydrogen system as well as present the sizing optimisation and simulation results of both systems. The results of the analyses also showed that the replacement of fossil fuel generator set with hydrogen technologies is technically feasible, but still not economically viable until reductions in the cost of hydrogen technologies are made in the future.

Khan and Iqbal (2005) also conducted a pre-feasibility study of using hybrid energy systems with hydrogen as an energy carrier for applications in Newfoundland, Canada was established using HOMER. A remote house having an energy consumption of 25 kWh day^{-1} and 4.73 kW peak power demands was

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considered as the stand-alone load. It was found that, a wind-diesel-battery hybrid system is the most suitable solution at present. However, a wind-fuel cell system would be a more attractive choice if the fuel cell cost reduces to 15% of its present market price. Significant advancement in small wind turbine technology and fuel cell research is needed before a wind-fuel cell system could be termed as commercially feasible.

This kind of research through HOMER model has also been experienced in Malaysia (Goh and Barsoum, 2006). The aim was to design the aspects of a hybrid power system of photovoltaic panels with the fuel cell and secondary batteries as backup units that will provide electricity for a small and remote located community. The accentuation on the hydrogen hybrid power system is exactly to obtain a reliable autonomous system with the optimization of the components size and the improvement of the capital cost. The results conclude that the replacement of the conventional system by a PEM fuel cell can keep the system reliability of supply at the same level while decreasing the environmental impact of the whole system.

The present study is proposed to design a hydrogen based power system to provide electricity for a coastal residential area in Kuala Terengganu, Malaysia (Fig. 1). The selected case study, which is being operating represent a power demand of 20 kWh day^{-1} and peak demand of 3.1 kW. The autonomous system used in this study is diesel generator-PV-wind system that right through upgraded to a standalone PV-wind-hydrogen and grid connected PV-wind-hydrogen energy system.

Hence, the rationale of this study is to examine the feasibility of integrating the hydrogen energy technologies in existing autonomous power system taking into consideration of technical and economic aspects. The system simulation performed is to estimate its operational characteristics, such as annual electricity production, annual loads served, excess electricity and capacity shortage. The proposed systems then was compared concerning on their operational characteristics and cost value in order to meet the existing user's power demand at a minimum cost of energy.

MATERIALS AND METHODS

Energy demand and resources:

Electrical load: Electrical load is one or more devices that consume electric energy. While, electricity demand is the rate at which electric energy is required by the load, measured in kilowatts (kW) (Demiroren and Yilmaz, 2010). The data were measured for the total hourly basis daily electrical load requirement of a residential of a small coastal village in Kuala Terengganu. The electrical load components include fluorescent lamps, ceiling fan, television, refrigerator and also washing machine which are the main components for a small house. The hourly load consumed by the house is presented in Fig. 2.

Solar radiation resources: Hourly solar radiation data for year 2006 was collected from Malaysian Meteorological Department (MMD). Using this data the monthly average daily solar radiation shown in Fig. 3 and long-term average annual solar radiation (1.28 kWh m^{-1} day^{-1}) were calculated for Kuala Terengganu. From the latitude information and solar radiation of the site under investigation, the HOMER software calculated the clearness index (a measure of the clearness or cloudiness of the atmosphere) shown in Fig. 3.

Fig. 1: Location of the research area

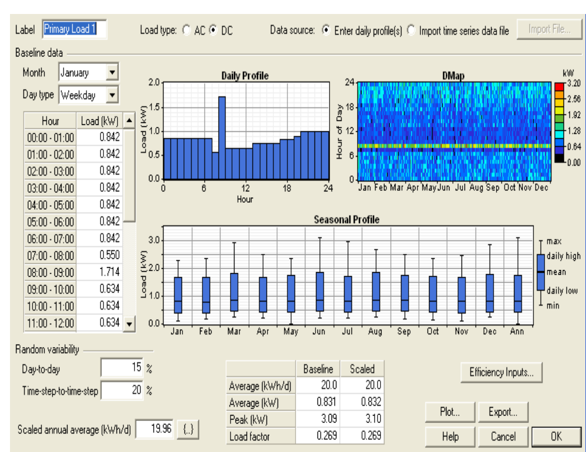


Fig. 2: Hourly load consumption for a house

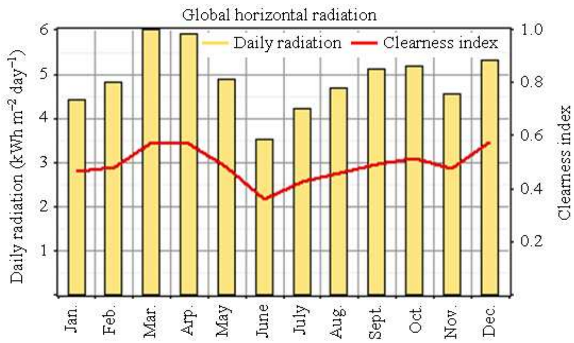


Fig. 3: Monthly average daily radiation and clearness index

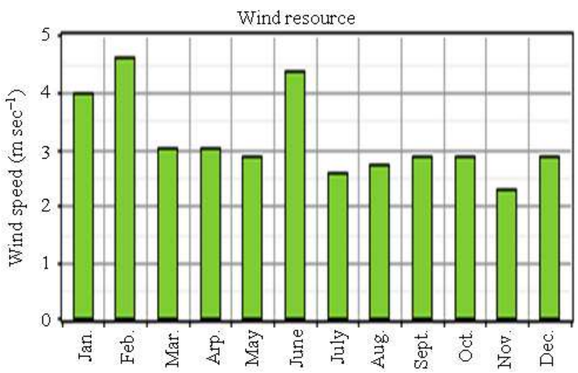


Fig. 4: Monthly average wind speed

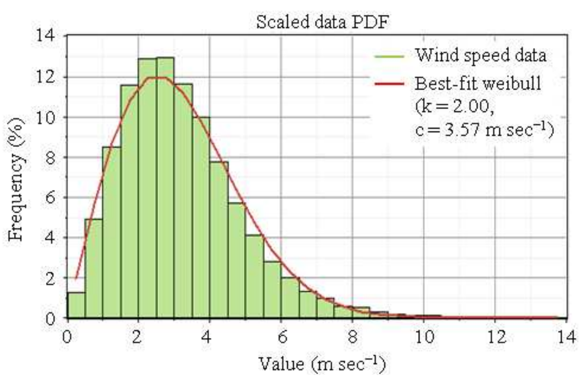


Fig. 5: Wind speed probability distribution

Wind resources: Hourly wind speed data for year 2006 also was collected from MMD and from this data the monthly average wind speeds were calculated, which, are shown in Fig. 4. It indicates that the annual average wind speed at hub height of 50 m in Kuala Terengganu is 3.16 m sec^{-1}. Figure 4 shows that in May to November except June, the wind speeds are lower than the annual average wind speed. The higher wind speed during the monsoon season explained these conditions.

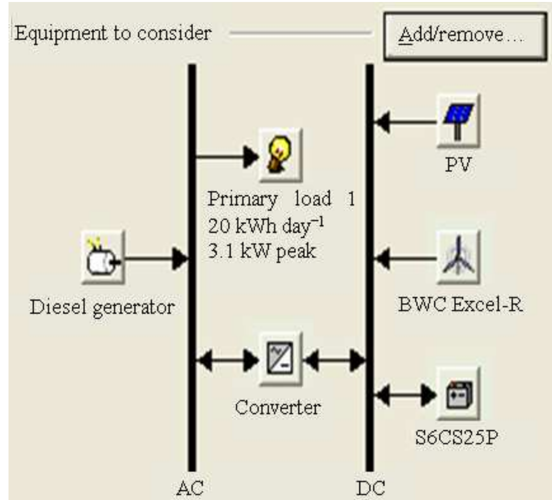


Fig. 6: PV-wind-diesel power system components

The wind data was analyzed using the Weibull distribution. The results show that the Weibull shape factor, k is 2.0 and scale factor, c is 3.57 m sec^{-1}. The autocorrelation factor (randomness in wind speed) is found to be 0.85. The diurnal pattern strength (wind speed variation over a day) is 0.25 (Fig. 5).

PV-wind-diesel power system: The schematic diagram of Photovoltaic (PV)-wind-diesel power system components are presented in Fig. 6. The energy system consists of diesel generator, PV arrays, wind turbine, battery and power converters. The cost, number of units to be used, capacity, operating hours and other specifications are needed to run the simulation using HOMER software. The details of the system components were obtained from manufacturers of the equipments and previous studies (Khan and Iqbal, 2005; Zoulias and Lymberopoulos, 2007; Goh and Barsoum, 2006; Demiroren and Yilmaz, 2010; Dalton and Lockington, 2009; Bergey Wind Power, 2009; Australian Government, 2009). The descriptions of these components are given below.

Diesel generator: The cost of a commercially available diesel generator may vary from \$250-\$500 kW^{-1} (Dalton and Lockington, 2009). For larger units per kW cost is lower and smaller units cost more. The 5 kW diesel generator at cost \$450 was being used as the peak power demand is less than 5 kW. Replacement and operational costs are assumed to be \$400 and \$0.150 h^{-1}, respectively. While, the lifetime is 15000 h. In this study no diesel generator (0 kW) or a 5 kW unit were used for simulation by HOMER.

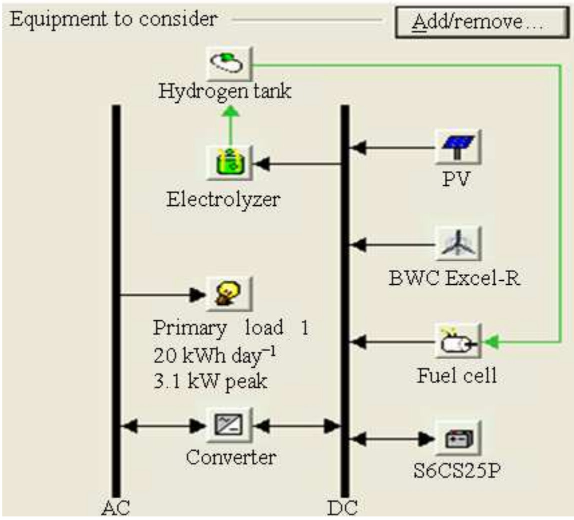


Fig. 7: Standalone PV-wind-hydrogen power system components

PV-array: The installation cost of PV arrays may vary from $6.00-$10.00/W. A 1 kW solar energy system installation and replacement costs are taken as $7000 and $6000, respectively (Dalton and Lockington, 2009). Various sizes were considered, ranges from 0-6 kW in this study. The lifetime of the PV arrays are taken as 20 years and no tracking system was included in the PV system.

Wind turbine: Availability of energy from the wind turbine depends greatly on wind variations. Therefore, wind turbine rating is generally much higher compared to the average electrical load. In this analysis, Bergey wind power's BWC Excel-R model was considered. It has a rated capacity of 8.1 kW and provides 48 V DC as output. Cost of one unit was considered to be $19,400 while replacement and maintenance costs were taken as $15,000 and $75 year^{-1} respectively (Bergey Wind Power, 2007). To allow the simulation program hit an optimum solution, provision for using several units (0, 12, 24, 26, 28, 30 and 32) were considered for the study location. The lifetime of the turbine was taken as 20 years.

Batteries: Batteries are considered as a major cost factor in small-scale stand-alone power systems. A battery bank of commercially available units, surrette-6CS25P model (6 V, 1156 Ah and 9645 kW) (Khan and Iqbal, 2005) was considered in this simulation. The estimated lifetime is 5 years and the cost of one battery is $1250 with a replacement cost of $1100 while the O and M cost is $0.02 year^{-1} were considered for this study. The battery stacks may contain a number of batteries range from 0-125 units.

Power converter: A power electronic converter needs to maintain flow of energy between the ac and dc components. For a 1 kW system the installation and replacement costs were taken as $800 and $750, respectively. Four different sizes of converters (0, 2, 5 and 7 kW) were considered for the simulation. Lifetime of a unit was considered to be 15 years with an efficiency of 90%.

Stand alone PV-wind-hydrogen power system: Subsequently, the conventional hybrid energy system has been upgraded to hybrid system of standalone PV-wind-hydrogen energy system that schematically designs as in Fig. 7. All the meteorological data that were used are same as the previous simulation.

The equipments needed to build the system are PV array, wind turbine, battery, fuel cell, electrolyzer, hydrogen tank and power electronic converters. In this hybrid energy system also, the type of wind turbine and battery were used same as the previous system, which are BWC Excel-R and Surrette 6CS25P, respectively. But different sizes were selected in order to define optimum combination of equipment dimensions. Stand alone PV-wind hydrogen system components are described more detail below.

PV-array: For this stand alone hybrid system, the PV capital, replacement and O and M costs, as well as component lifetime described under 3.2 were used. The considered sizing range from 0-40 kW.

Wind turbine: In the optimization process, the costs of the wind turbine were the same as the one used in previous energy system. The quantity of wind turbines considered for this systems were 0, 1, 2, 24, 26, 30 and 32 units.

Electrolyzer: Currently production cost of electrolyzers is $1500-$3000 kW^{-1}. With improvements in polymer technology, control systems and power electronics it is expected that costs would reduce much in 10 years (Dalton and Lockington, 2009). In this analysis, various sizes of electrolyzers (0-50 kW) were considered. A 1 kW system is associated with $2000 capital, $1500 replacement and $20 maintenance cost. Lifetime is considered as 25 years with efficiency 75%.

Power converter: Power electronic converter description is similar as describe above. For a 1 kW system the installation and replacement costs are taken as \$800 and \$750, respectively. Three different sizes of converter (1.5, 3.5 and 5 kW) were taken in the model.

Fuel cell system: The cost of fuel cell varies greatly depending on type of technology, reformer, auxiliary equipments and power converters. At present, a fuel cell cost varies from \$3000-\$6000 kW^{-1} (Dalton and Lockington, 2009). Here, the capital, replacement and operational costs were taken as \$3000, \$2500 and \$0.020/h for a 1 kW system, respectively. Five different sizes of fuel cells were taken in the simulation process: 0 (no fuel cell used), 1.5, 3.5 and 5 kW. Fuel cell lifetime and efficiency were considered to be 40,000 h and 50%, respectively.

Hydrogen tank: Cost of a tank with 1 kg of hydrogen capacity was assumed to be \$1300. The replacement and operational costs were taken as \$1200 and \$15 $year^{-1}$, respectively. Seven different sizes (0, 1, 2.5, 3, 7.5, 10 and 15 kg) were included, to widen the search space for a cost effective configuration and the lifetime was also considered as 25 years.

Grid connected PV-wind-hydrogen power system: Afterward, the grid-connected PV-wind-hydrogen analysis has been done to review the ability of electricity production from the renewable sources, photovoltaic and wind. In this system electricity from the grid was used to supply power to the electrolyzer device in order to produce hydrogen during the deficient in power from PV and wind. The schematic design appears in Fig. 8.

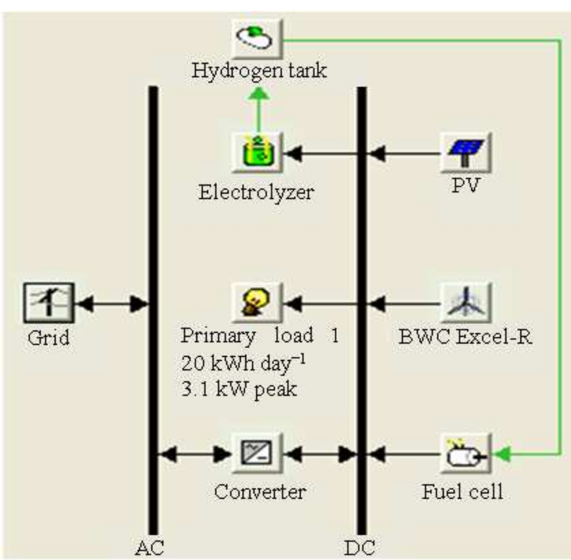


Fig. 8: Grid connected PV-wind hydrogen power system components

Such system forms of the similar equipments as standalone PV-wind-hydrogen that mentioned before. Except, the power transmission or grid system was attached. The single rate that refers to the fix power price, sellback rate and demand rate was set for the case of residential consumers. The fix power is 0.1\$ kWh^{-1} while the sellback rate and demand rate are 0.05\$ kWh^{-1} and 0.00\$ kWh^{-1} $month^{-1}$, respectively.

The grid system works in two conditions. When the renewable energy system produces more power that the house needs, the excess power is fed back into the grid. However, when the does not produce enough power, then the power can be drawn from the grid.

RESULT AND DISCUSSION

PV-wind-diesel system simulation: For hybrid PV-wind-diesel energy system, the equipments needed to build the system were diesel generator, PV array, wind turbine, batteries and power electronic converter with the type and quantity that mentioned before. The HOMER simulation tool was used to optimize the sizes of different hardware components in the PV-wind-diesel system, taking into account the technical characteristics of system operation and minimizing total net present cost of the system. The simulation of the system completed with in 1 min. The optimization results of this power system are show in Fig. 9.

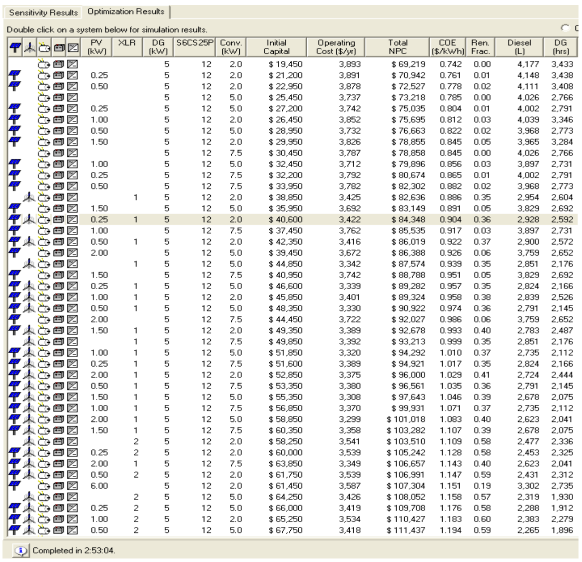
The least Cost Of Energy (COE), \$0.74 kWh^{-1} resulted from the 5 kW diesel generator alone without contribution from renewable sources. If considered the system, which is included the renewable energies is fifteenth least COE as \$0.90 kWh^{-1}, resulted from the combination of 5 kW diesel generator, 0.25 kW of PV array, 1 unit of wind turbine, 12 unit of batteries and 2 kW converter. The diesel used for first system is 4,177 L, while the second system is 2,928 L. Consequently, the consumption of diesel fuel can be reduced about 30.0% with involvement of renewable resources.

The distribution of annualized cost for each component of the hybrid PV-wind-diesel energy system is presented in Table 1.

The capital cost, total Net Present Value (NPC) and COE of the systems are \$40,600, \$84,348 and \$0.90 kWh^{-1} respectively. The most expensive cost draws from the diesel generator. Although the capital for the generator is just \$450, but the high cost of diesel fuel, \$24,332 sums it up to \$30,427. Wind turbine is in the second placed with the cost of \$25,453, followed by battery and converter with \$22,001 and \$4,511, respectively. The least cost device is PV-array that contributes \$1,956 to the overall system. The allocation of each device can be seen clearly from Fig. 10.

Table 1: Annualized cost for main components of the PV-wind-diesel system

Component	Capital ($)	Replacement ($)	O and M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	1,750	468	0	0	-262	1,956
Wind turbine	19,400	6,259	959	0	-1,165	25,453
Diesel generator	450	739	4,970	24,332	-63	30,427
Batteries	15,000	9,820	0	0	-2,819	22,001
Converter	4,000	0	511	0	0	04,511
System	40,600	17,285	6,440	24,332	-4,310	84,348



PV (kW)	XLR	DG (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
		5	12	2.0	$ 19,450	3,893	$ 69,219	0.742	0.00	4,177	3,433
0.25		5	12	2.0	$ 21,200	3,891	$ 70,942	0.761	0.01	4,148	3,438
0.50		5	12	2.0	$ 22,950	3,878	$ 72,527	0.778	0.02	4,111	3,408
		5	12	5.0	$ 25,450	3,737	$ 73,218	0.785	0.00	4,026	2,766
0.25		5	12	5.0	$ 27,200	3,742	$ 75,035	0.804	0.01	4,002	2,791
1.00		5	12	2.0	$ 26,450	3,852	$ 75,695	0.812	0.03	4,039	3,346
0.50		5	12	5.0	$ 28,950	3,732	$ 76,663	0.822	0.02	3,968	2,773
1.50		5	12	2.0	$ 29,950	3,826	$ 78,855	0.845	0.05	3,965	3,284
		5	12	7.5	$ 30,450	3,787	$ 78,858	0.845	0.00	4,026	2,766
1.00		5	12	5.0	$ 32,450	3,712	$ 79,896	0.856	0.03	3,897	2,731
0.25		5	12	7.5	$ 32,200	3,792	$ 80,674	0.865	0.01	4,002	2,791
0.50		5	12	7.5	$ 33,950	3,782	$ 82,302	0.882	0.02	3,968	2,773
	1	5	12	2.0	$ 38,850	3,425	$ 82,636	0.886	0.35	2,954	2,604
1.50		5	12	5.0	$ 35,950	3,692	$ 83,149	0.891	0.05	3,829	2,692
0.25	1	5	12	2.0	$ 40,600	3,422	$ 84,348	0.904	0.36	2,928	2,592
1.00		5	12	7.5	$ 37,450	3,762	$ 85,535	0.917	0.03	3,897	2,731
0.50	1	5	12	2.0	$ 42,350	3,416	$ 86,019	0.922	0.37	2,900	2,572
2.00		5	12	5.0	$ 39,450	3,672	$ 86,388	0.926	0.06	3,759	2,652
	1	5	12	5.0	$ 44,850	3,342	$ 87,574	0.939	0.35	2,851	2,176
1.50		5	12	7.5	$ 40,950	3,742	$ 88,788	0.951	0.05	3,829	2,692
0.25	1	5	12	5.0	$ 46,600	3,339	$ 89,282	0.957	0.35	2,824	2,166
1.00	1	5	12	2.0	$ 45,850	3,401	$ 89,324	0.958	0.38	2,839	2,526
0.50	1	5	12	5.0	$ 48,350	3,330	$ 90,922	0.974	0.36	2,791	2,145
2.00		5	12	7.5	$ 44,450	3,722	$ 92,027	0.986	0.06	3,759	2,652
1.50	1	5	12	2.0	$ 49,350	3,389	$ 92,678	0.993	0.40	2,783	2,487
	1	5	12	7.5	$ 49,850	3,392	$ 93,213	0.999	0.35	2,851	2,176
1.00	1	5	12	5.0	$ 51,850	3,320	$ 94,292	1.010	0.37	2,735	2,112
0.25	1	5	12	7.5	$ 51,600	3,389	$ 94,921	1.017	0.35	2,824	2,166
2.00	1	5	12	2.0	$ 52,850	3,375	$ 96,000	1.029	0.41	2,724	2,444
0.50	1	5	12	7.5	$ 53,350	3,380	$ 96,561	1.035	0.36	2,791	2,145
1.50	1	5	12	5.0	$ 55,350	3,308	$ 97,643	1.046	0.39	2,678	2,075
1.00	1	5	12	7.5	$ 56,850	3,370	$ 99,931	1.071	0.37	2,735	2,112
2.00	1	5	12	5.0	$ 58,850	3,299	$ 101,018	1.083	0.40	2,623	2,041
1.50	1	5	12	7.5	$ 60,350	3,358	$ 103,282	1.107	0.39	2,678	2,075
	2	5	12	2.0	$ 58,250	3,541	$ 103,510	1.109	0.58	2,477	2,336
0.25	2	5	12	2.0	$ 60,000	3,539	$ 105,242	1.128	0.58	2,453	2,325
2.00	1	5	12	7.5	$ 63,850	3,349	$ 106,657	1.143	0.40	2,623	2,041
0.50	2	5	12	2.0	$ 61,750	3,539	$ 106,991	1.147	0.59	2,431	2,312
6.00		5	12	2.0	$ 61,450	3,587	$ 107,304	1.151	0.19	3,302	2,735
	2	5	12	5.0	$ 64,250	3,426	$ 108,052	1.158	0.57	2,319	1,930
0.25	2	5	12	5.0	$ 66,000	3,419	$ 109,708	1.176	0.58	2,288	1,912
1.00	2	5	12	2.0	$ 65,250	3,534	$ 110,427	1.183	0.60	2,383	2,279
0.50	2	5	12	5.0	$ 67,750	3,418	$ 111,437	1.194	0.59	2,265	1,896

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Fig. 9: The simulation results for PV-wind-diesel energy system

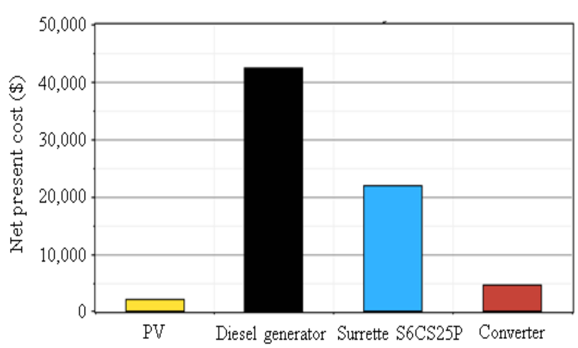


Fig. 10: Cost components of PV-Wind-Diesel System

The PV-wind-diesel hybrid system also simulated in order to evaluate its operational characteristics, namely annual electrical energy production, annual electrical load served, excess electricity, renewable energy fraction, capacity shortage and unmet load.

The strategy taken in this simulation is to ensure the power generator provide enough power to meet the demand. The renewable energy sources in collaboration with the diesel generator were evaluated to determine the feasibility of the system.

Table 2: Operational characteristics of the PV-wind-diesel hybrid system

Annual electricity production	kWh year^{-1}	Percent
PV-array	87	1.00
Diesel generator	7,566	64.00
Wind turbine	4185	35.00
Total production	11,838	100.00
Annual electrical load served		
AC primary load served	7,299	100.00
Total	7,299	100.00
Other		
Excess electricity	1,129	9.82
Unmet electric load	0.543	0.01
Capacity shortage	1.17	0.02
Renewable fraction	0.361	

The values related to the electricity production and load served by the system are summarized in Table 2. The results of the simulation showed that the PV-wind-diesel hybrid system had a total annual electrical energy production of 11,838 kWh year^{-1}. The biggest contributor is diesel generator comprise of 63% equal to 7,566 kWh/year. The renewable energy fraction is 0.361. The contribution of renewable sources which come from PV-array and wind turbine produce 1% (87 kWh year^{-1}) and 35% (4,185 kWh year^{-1}), respectively. Besides that, it can be seen that approximately 9.82% (1144 kWh year^{-1}) was neglected. These excess energy can be manipulated to increase renewable energy penetration by stored it in the form of compressed hydrogen and drive a PEM fuel cell will be discussed in the standalone PV-wind hydrogen energy system.

The trend of monthly electricity production is shown in Fig. 11. The wind is highly potential in three months, January, February and June. Hence, diesel generator operated frequently in other months. The condition is occurs due to the high nighttime load, which enables the operation of diesel generator because wind and PV energy stored in batteries is not adequate to serve the load during night time.

Stand alone PV-wind-hydrogen system simulation: The design of stand-alone power systems with hydrogen energy involves different energy components sizes, with regards to the cost of energy and overall

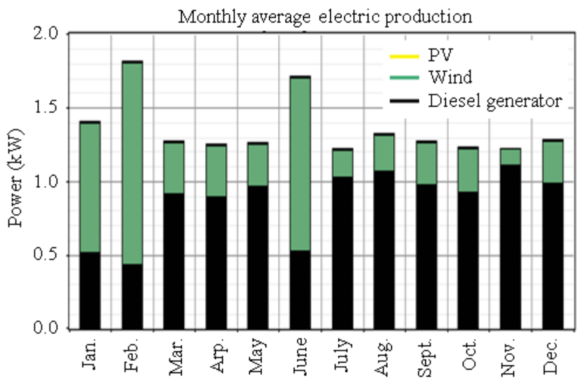


Fig. 11: Monthly electricity production trend of the system

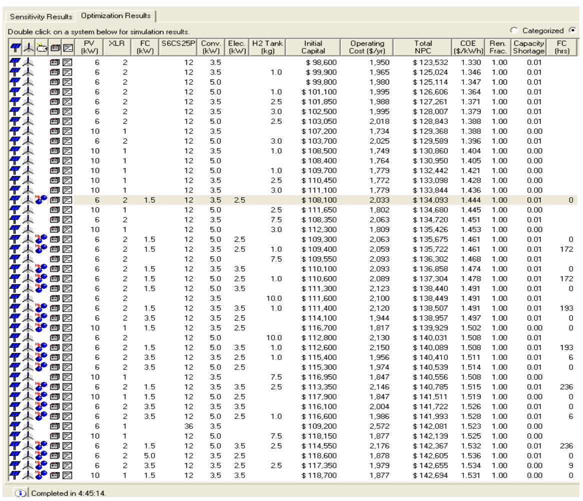


Fig. 12: The simulation results for standalone PV-wind-hydrogen energy system

system performance. The HOMER simulation tool was used to optimize the sizes of different hardware components in the PV-wind-hydrogen system, taking into account the technical characteristics of system operation and minimizing total NPC of the system.

The simulation for this system was difficult due to the quantity of equipment involved to build the system and overall simulation takes around 4 h and 45 min to be accomplished. The optimization results for this analysis shown in Fig. 12. It illustrates that the most optimum results obtained for this system comprises of 6 kW of PV array, 2 unit of wind turbine, 12 units of batteries and 3.5 kW converter so as to generate the minimum COE, \$1.33 kWh^{-1}. Although renewable sources (wind and PV) involved in the power generation, but no hydrogen was produced at all in this system.

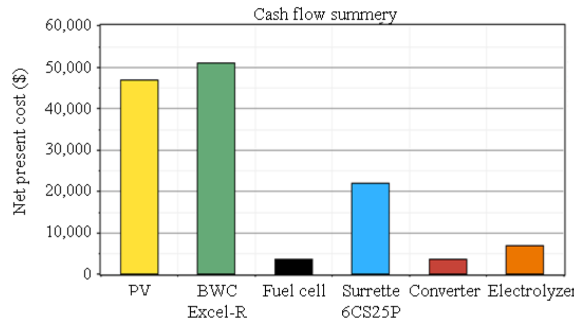


Fig. 13: Cost for component of standalone PV-wind-hydrogen system

Hence, the system that encompass of 6 kW of PV array, 2 unit of wind turbine, 1.5 kW of fuel cell, 12 unit of batteries, 3.5 kW converter as well as 2.5 kW of electrolyzer that generate fifteenth lowest COE at \$1.44/kWh is being concentrated in this study due to the potential of hydrogen energy. The difference in COE value of both systems is not too much, so this system is also considered feasible.

In this PV-wind-hydrogen energy system, the PV array capacity was enlarge in relation to the one used in the PV-wind diesel system, from 2.5-6 kW, in order to fully replace the diesel generator usage. The hydrogen tank is excluded from the system, as the storage tank is considered within the electrolyzer model and the hydrogen is supplied to the fuel cell directly from the electrolyzer.

The total capital costs and total NPC calculated for this system were \$108,100 and \$134,093 respectively (Table 3).

Wind turbine dominated the cost with \$50,905, followed by PV with \$46,934. Battery had contributed \$22,001 which was the third largest contributor for this system. Subsequently, electrolyzer, converter and fuel cell cost about \$6,913, \$3,691 and \$3,648, respectively. The allocation of each device can be seen clearly from Fig. 13.

The values related to the electricity production and load served by the system are summarize in Table 4. The results of the simulation showed that the PV-wind-hydrogen system had a total annual electrical energy production of 17,414 kWh year^{-1}. The biggest contributor is wind turbine with 9,435 kWh year^{-1} (56%) followed by PV-array of 7,979 kWh year^{-1} (46%). Fuel cell not contributes to the electricity generation at all.

The consumption of electricity about 60% (7,264 kWh year^{-1}) goes to AC primary load served and 40% (4,931 kWh year^{-1}) goes to electrolyzer load. The

Table 3: Annualized cost for main components of the stand alone PV-wind-hydrogen system

Component	Capital ($)	Replacement ($)	O and M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	42,000	11,225	0	0	-6,291	46,934
BWC Excel-R	38,800	12,518	1,918	0	-2,330	50,905
Fuel cell	4,500	0	0	0	-852	3,648
Surrette 6CS25P	15,000	9,820	0	0	-2,819	22,001
Converter	2,800	1,095	0	0	-204	3,691
Electrolyzer	5,000	1,565	639	0	-291	6,913
System	108,100	36,223	2,557	0	-12,787	134,093

Table 4: Operational characteristics of the stand alone PV-wind-hydrogen system

Annual electricity production	kWh year^{-1}	Percent
PV-array	7,979	46.0
Wind turbine	9,435	54.0
Fuel cell	0	0.0
Total production	17,414	100.0
Consumption		
AC primary load served	7,264	60.0
Electrolyzer load	4,931	40.0
Total	12,194	100.0
Other		
Excess electricity	3,600	20.7
Unmet electric load	36.5	0.5
Capacity shortage	49.8	0.7

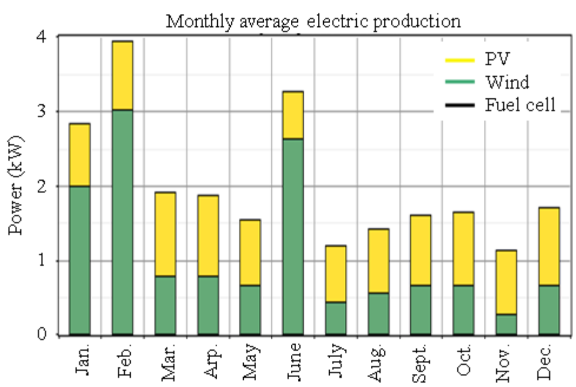


Fig. 14: Monthly electricity production trend of the stand alone PV-wind-hydrogen system

difference of annual electricity production and consumption given the value of excess electricity for this system is 3,600 kWh year^{-1} (20.7%)

The trend of monthly electricity production by these sources of energy is summarized in Fig. 13. The electricity from wind resources is higher in January, February and June.

The monthly hydrogen production from 2.5 kW electrolyzer can be seen in Fig. 15. The apparent months probable to produce hydrogen are January, February and June. The hydrogen production comes from potential wind energy in that particular month. The amount of yearly hydrogen production is 93.8 kg year^{-1} make the average cost of hydrogen is 112$ kg^{-1}.

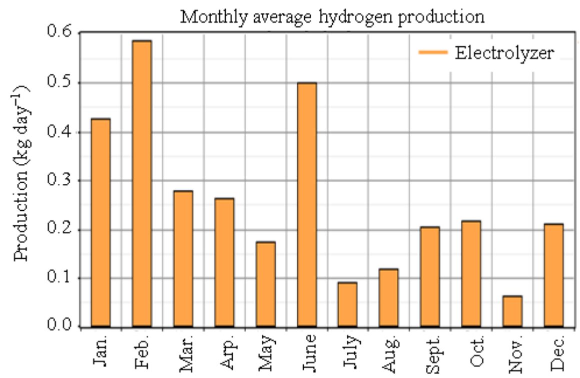
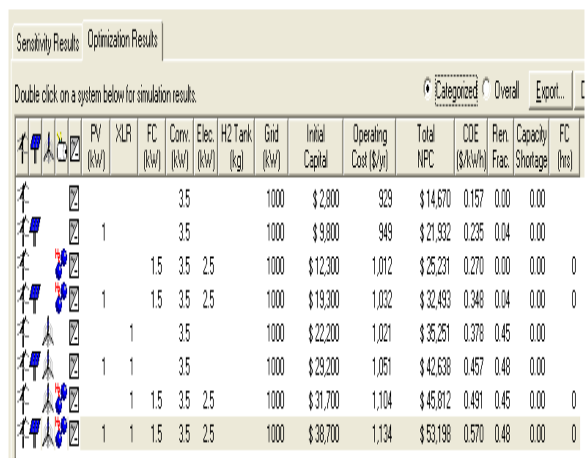


Fig. 15: Monthly hydrogen production of the stand alone PV-wind-hydrogen system



Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

Categorized | Overall | Export...

PV (kW)	XLR	FC (kW)	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	FC (hrs)
			3.5			1000	$ 2,800	929	$ 14,670	0.157	0.00	0.00	
1			3.5			1000	$ 9,800	949	$ 21,932	0.235	0.04	0.00	
		1.5	3.5	2.5		1000	$ 12,300	1,012	$ 25,231	0.270	0.00	0.00	0
1		1.5	3.5	2.5		1000	$ 19,300	1,032	$ 32,493	0.348	0.04	0.00	0
	1		3.5			1000	$ 22,200	1,021	$ 35,251	0.378	0.45	0.00	
1	1		3.5			1000	$ 29,200	1,051	$ 42,638	0.457	0.48	0.00	
	1	1.5	3.5	2.5		1000	$ 31,700	1,104	$ 45,812	0.491	0.45	0.00	0
1	1	1.5	3.5	2.5		1000	$ 38,700	1,134	$ 53,198	0.570	0.48	0.00	0

Fig. 16: The simulation results for grid connected PV-wind-hydrogen energy system

Grid connected PV-wind-hydrogen system simulation: The simulation for this system took around 45 min to be accomplished. The optimization results for this analysis shown in Fig. 16. It illustrates that the most optimum results obtained for this system comprises of grid system 1000 and 3.5 kW converter so as to generate the minimum COE, $0.157 kWh^{-1}.

Hence, the system that encompass of 1 kW of PV array, 1 unit of wind turbine, 1.5 kW of fuel cell, 3.5 kW converter as well as 2.5 kW of electrolyzer that

Table 5: Annualized cost for main components of the grid connected PV-wind-hydrogen system

Component	Capital ($)	Replacement ($)	O and M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	7,000	1,871	0	0	-1,048	7,822
BWC Excel-R	19,400	6,259	959	0	-1,165	25,453
Fuel cell	4,500	0	0	0	-852	3,648
Grid	0	0	5,670	0	0	5,670
Converter	2,800	1,095	0	0	-204	3,691
Electrolyzer	5,000	1,565	639	0	-291	6,913
System	38,700	10,790	7,268	0	-3,561	53,19

Table 6: Operational characteristics of the grid connected PV-wind-hydrogen system

Annual electricity production	kWh year^{-1}	Percent
PV-array	373	4.00
Wind turbine	4,718	45.00
Fuel cell	0	0.00
Grid purchases	5,460	52.00
Total production	10,550	100.00
Consumption		
DC primary load served	7,300	77.00
Electrolyzer load	144	2.00
Grid sales	2,048	22.00
Total	9,492	100.00
Other		
Excess electricity	11.4	0.11
Unmet electric load	0.00	0.00
Capacity shortage	0.00	0.00
Renewable fraction	48.3	

Table 7: NPC and COE for all three systems

System	NPC ($)	COE ($/kWh)
PV-wind diesel energy system	84,348	0.90
Stan alone PV-wind-hydrogen energy system	134,093	1.44
Grid connected PV-wind-hydrogen energy system	53,197	0.57

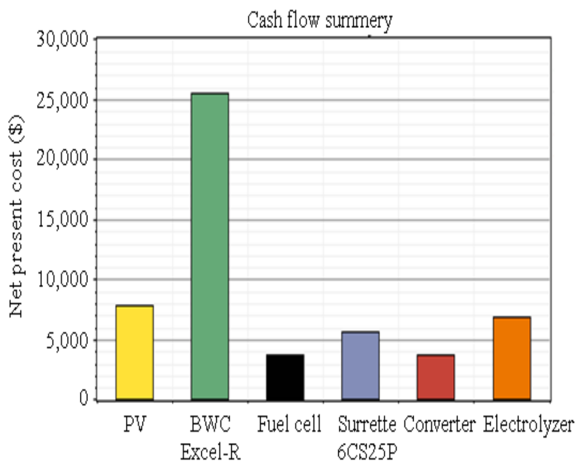


Fig. 17: Cost component of grid connected PV-wind-hydrogen system

generate eighth lowest COE at $0.57 kWh^{-1} is being concentrated in this study due to the potential of hydrogen energy. The difference in COE value of both systems is too much, even though this system is also considered feasible. The battery is excluded from the system, as the system is connected to the grid.

The total capital costs and total NPC calculated for this system were $38,700 and $53,197 respectively (Table 5). Wind turbine dominated the cost with $25,453, followed by PV- array with $7,822. The grid cost $5,670 which was the third largest contributor for this system. Subsequently, electrolyzer, converter and fuel cell cost about $6,913, $3,691 and $3,648, respectively. The cost contribution of each device can be seen clearly from Fig. 17.

The value related to the electricity production and load served by the system are summarized in Table 6. The results of the simulation showed that the PV-wind-hydrogen system had a total annual electrical energy production of 10,550 kWh year^{-1}. The biggest contributor is grid system with 5,460 kWh year^{-1} (52%) and followed by wind turbine with 4,718 kWh/year (45%) and PV-array of 372 kWh year^{-1} (4%). Fuel cell not contributes to the electricity generation at all. The consumption of electricity about 77% (7,300 kWh year^{-1}) goes to DC primary load served and 2% (145 kWh year^{-1}) goes to electrolyzer load.

The electricity sells to grid accounted for 2,047 kWh year^{-1} (22%) as well. The difference of annual electricity production and consumption given the value of excess electricity for this system is 11.3 kWh year^{-1} (0.11%).

The trend of monthly electricity production by this source of energy is summarized in Fig. 18. The electricity from wind resources is higher in January, February and June and the rest mostly come out from grid.

The monthly hydrogen production from 2.5 kW electrolyzer can be seen in Fig.. 19. The apparent months probable to produce hydrogen are January, February and June. The hydrogen production comes from potential wind energy in that particular month. The amount of yearly hydrogen production is 2.74 kg year^{-1}. whilst, the average cost of hydrogen is 1,517$ kg^{-1}.

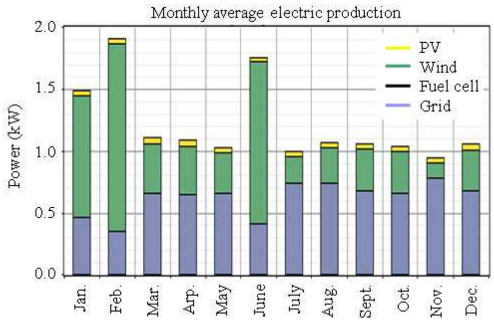


Fig. 18: Monthly electricity production trend of the grid connected PV-wind-hydrogen system

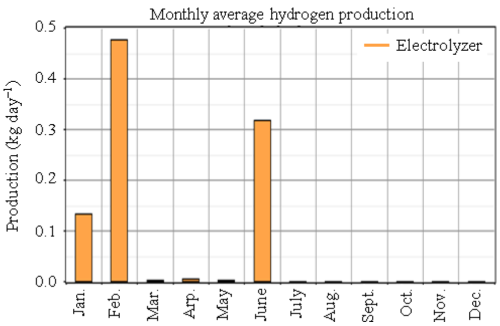


Fig. 19: Monthly hydrogen production for the grid connected PV-wind-hydrogen system

Comparison of all systems for the most cost effective system: Comparison of the entire systems that had been simulated by HOMER, it was found that the grid connected hybrid PV-wind-hydrogen energy system had the lowest total NPC and COE, $53,197 and $0.57 kWh^{-1} (Table 7) respectively that makes it the most cost effective system.

The stand alone PV-wind-hydrogen cannot defeat the grid connected PV-wind-hydrogen energy system in economical evaluation. This is probably due to the higher usage of expensive equipment among all the equipment involved. The grid systems that serve as battery eliminate the need for a battery backup for when the sun doesn't shine or the wind doesn't blow (Australian Government, 2009). In effect, the maintenance costs for the system will be less and make the COE cheaper.

CONCLUSION

The comparisons prove that grid connected PV-wind-hydrogen energy system had the lowest total NPC and COE, which was $53,197 and $0.57 kWh^{-1} accordingly that makes it the most cost effective system and followed by PV-wind-diesel and stand alone PV-wind-hydrogen system. Consequently, it is the most suitable system at lower cost to be developed in this area. However, the hydrogen energy is feasible by standalone system rather than grid system.

Hence, it can be concluded that the hydrogen-based system can become a favorable system without aid from the grid system and bring advantage in technical and economic point of view and also suitable to be applied in the coastal residential application as energy carrier if only the current cost of wind turbine and hydrogen system technology have been reduced to its minimum rate.

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