PAPER • OPEN ACCESS

Sizing and economic analysis of stand alone photovoltaic system with hydrogen storage

To cite this article: N D Nordin and H A Rahman 2017 *IOP Conf. Ser.: Earth Environ. Sci.* **93** 012068

IOP Conf. Series: Earth and Environmental Science **93** (2017) 012068 doi:10.1088/1755-1315/93/1/012068

Sizing and economic analysis of stand alone photovoltaic system with hydrogen storage

N D Nordin[1,2] and H A Rahman[1,2,3]

[1]Centre of Electrical Energy Systems, Institute of Future Energy, Universiti Teknologi Malaysia, 81300, Johor, Malaysia
[2]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81300, Johor, Malaysia

E-mail: hasimah@fke.utm.my

Abstract. This paper proposes a design steps in sizing of standalone photovoltaic system with hydrogen storage using intuitive method. The main advantage of this method is it uses a direct mathematical approach to find system's size based on daily load consumption and average irradiation data. The keys of system design are to satisfy a pre-determined load requirement and maintain hydrogen storage's state of charge during low solar irradiation period. To test the effectiveness of the proposed method, a case study is conducted using Kuala Lumpur's generated meteorological data and rural area's typical daily load profile of 2.215 kWh. In addition, an economic analysis is performed to appraise the proposed system feasibility. The finding shows that the levelized cost of energy for proposed system is RM 1.98 kWh. However, based on sizing results obtained using a published method with AGM battery as back-up supply, the system cost is lower and more economically viable. The feasibility of PV system with hydrogen storage can be improved if the efficiency of hydrogen storage technologies significantly increases in the future. Hence, a sensitivity analysis is performed to verify the effect of electrolyzer and fuel cell efficiencies towards levelized cost of energy. Efficiencies of electrolyzer and fuel cell available in current market are validated using laboratory's experimental data. This finding is needed to envisage the applicability of photovoltaic system with hydrogen storage as a future power supply source in Malaysia.

1. Introduction

World's electricity production mostly depends on coal, oil and natural gas as power supply. Due to limited fuels reserves, fuels' unstable prices and global warming risks, the interest in renewable energy (RE) sources increases significantly. The importance of RE is not only to reduce dependence on fossil fuels, but it is also environmentally-friendly, free, and abundantly available [1].

Compared to other alternatives electricity generation available in Malaysia, photovoltaic (PV) system is the most promising RE. However, due to intermittence of solar irradiation, standalone photovoltaic (SAPV) system needs a backup energy storage system to ensure continuous power supply.

Among wide varieties of technology options for electrical energy storage system, hydrogen storage (HS) has been receiving a lot of attention due to clean quality, insightful environmental benefits, and its' regenerative hydrogen feature. Integrating PV with HS leads to construction of non-polluting generation system and reducing emissions. Introduction of HS in a small-scale power application could be one of the big breakthroughs to introduce hydrogen economy as an environmental friendly electrical storage system.

In SAPV system, hydrogen is produced from water by electrolysis powered by electricity generated from PV, and then stored in hydrogen tank. When load demand is higher than generated PV generation, the stored hydrogen and air are fed into a fuel cell (FC), then the reverse process of electrolysis takes place, and energy is supplied to consumers [2,3].

However, despite being high potential and endowed with high irradiation [4], SAPV with HS system is still being explored and has not being successfully applied in Malaysia due to high initial cost and requirement of large space area. Hence, further study on design and feasibility of SAPV with HS is necessary. Before any installation, it is crucial to ensure the recommended SAPV and HS system will not oversize/undersize, and designers have to investigate system viability in preliminary design. In order to efficiently and economically utilize solar energy, optimization in system sizing is necessary so that the proposed system can operate in optimum condition in terms of investment and reliability [5]. Designers also have to forecast electricity consumption and generation in order to ensure the proposed system can fulfill energy demand.

During the past ten years, more information is available on optimization of SAPV with HS system. A method to determine optimum design, control strategy, economic and performance analysis of SAPV with HS system at Aswan, Egypt was proposed [6]. The paper iteratively found optimum size for system's components that able to match four different load profiles (load profile of January, April, July, and October). By using autonomous simulation built from operation control strategies and energy balance mathematical modeling, loss of power supply probability (LPSP) was used to analyze system reliability. Detailed economic analysis was performed and presented in levelized cost of energy (LCOE). However, the sizing method is too complex and will need long calculation time.

In 2012, another authors [7] presented a direct mathematical approach to find optimal size of SAPV with HS and battery system based on load consumption and irradiation curve from selected site [6]. By using the calculated system size, the whole system was simulated using mathematical model in Matlab Simulink. Detailed energy flow was provided and energy flow to battery and HS depended on value of limit charge and discharge power. This work presented an extensive and insightful simulation results, but no economic analysis to validate system feasibility was performed.

In 2013 [2], the authors determined the size of SAPV with hydrogen and battery system using Simulink Design Optimization Method existed in Matlab. However, the paper mainly focused on modeling and control strategies for the system. The optimization was done only to satisfy load and maintain hydrogen energy reserve and battery's state of charge, with simple total cost comparison between SAPV/battery and SAPV/hydrogen storage system. System feasibility was not performed on the proposed system.

This paper presents sizing and economic analysis of SAPV system with HS using intuitive method. By using this method, sizing task becomes much simpler by using direct mathematical approach to find system size. A case study is conducted using Kuala Lumpur meteorological data and typical rural area daily load profile of 2.215 kWh. Finally, an economic analysis using LCOE is calculated to determine the system feasibility and to economically utilize the PV and HS system [5,8]. The results are compared to the calculated results using published method in 2014 [9], based on same initial cost rating, load and PV configurations. A sensitivity analysis is performed to investigate the effect of electrolyzer and fuel cell efficiencies towards levelized cost of energy in the future. Current PV panel and hydrogen storage efficiencies are validated using pre-processed measured data from an installed photovoltaic system in Universiti Teknologi Malaysia and laboratory's experimental data. The contribution of this paper is to introduce the integration of PV with HS, using prior information, assessment, and extensive sizing steps on each component with respect to Malaysia's local environment. This paper also envisage the applicability of photovoltaic system with hydrogen storage as a future power supply source in Malaysia

2. System configuration

The proposed configuration for the SAPV with HS system in Malaysia is shown in figure 1. During daytime, PV array converts solar irradiation into DC power. If PV array produces higher power than load demand, the surplus power will be transferred to electrolyzer. Electrolyzer uses the excess power to decomposition water into hydrogen and oxygen gasses. The hydrogen gas will be stored in hydrogen tank, and oxygen releases to the air. However, during insufficient PV generation, fuel cell draws hydrogen from tank and oxygen from the air, and converts both gasses into water to produce additional power for load. DC bus voltage is nominal voltages for PV array, HS, and DC appliance. Inverter converts DC power into AC power to match AC bus and AC appliances.

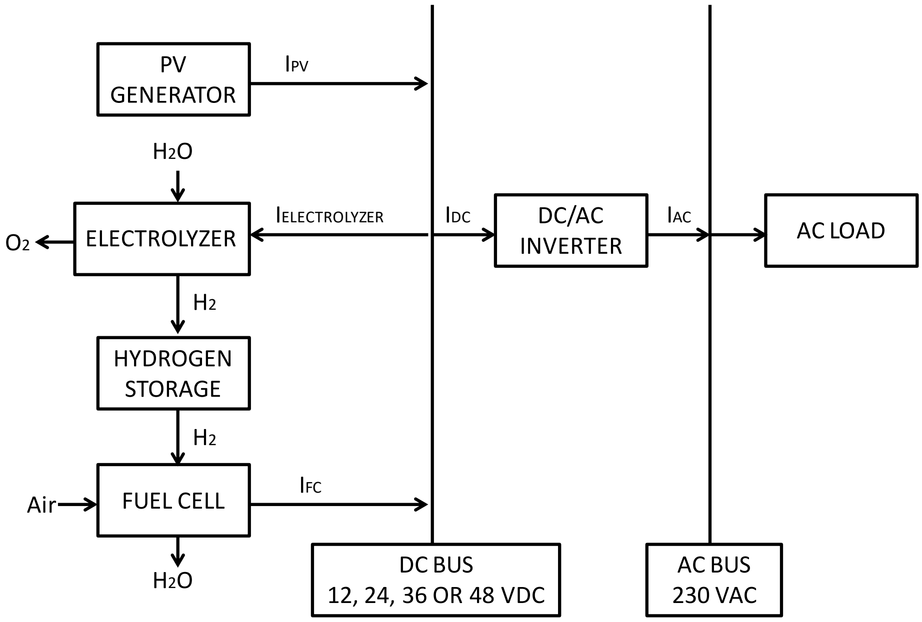

Figure 1. System configuration for SAPV with HSS.

2.1. Solar energy resources forecast

Accuracy in predicting PV generation plays a great significance in system design, where energy output from the proposed system is predicted by an inclusive study on site's meteorological condition [10]. In this paper, meteorological data was imported from Meteonorm 6.1. Table 1 shows the annual global irradiation for each states in Malaysia. In the other hand, the average monthly annual irradiation and PSH data for Kuala Lumpur is presented in table 2 [11]. It is shown that the state's annual global irradiation is 1655.59 kWh/m^2, maximum average annual irradiance over a year, H_{Smax} is 205.511 W/m^2 (March) and the lowest monthly daily's peak sun hour, PSH_{lowest} is 4.081 h/day (November).

Table 1. Annual global irradiation in Malaysia [11].

State	Global Irradiation, kWh/m²
Kuala Lumpur	1655.59
Labuan	1792.10
Putrajaya	1654.60
Terengganu	1771.49
Johor	1637.32
Kedah	1795.90
Kelantan	1782.71
Negeri Sembilan	1650.40
Pahang	1675.50
Perak	1760.00
Perlis	1788.50

Pulau Pinang	1794.90
Sabah	1733.23
Sarawak	1579.58

Table 2. Monthly average annual irradiation and daily's peak sun hour in Kuala Lumpur [11].

Month	Average Annual Irradiance, W/m²	PSH (h)
January	179.839	4.319
February	202.976	4.871
March	205.511	4.945
April	199.861	4.800
May	194.892	4.681
June	187.639	4.513
July	188.978	4.535
August	186.962	4.487
September	187.778	4.513
October	190.860	4.584
November	171.944	4.127
December	170.027	4.081

2.2. Load demand

Table 3 presents load profile for a house in rural area in Malaysia. It is assumed that the daily load remains the same throughout the year [12]. The AC load profile of 2.215 kWh consists of different types of home appliances. The hourly load profile is as illustrated in figure 2 with an assumption that the daily energy requirement remains the same throughout the year [9,12-15].

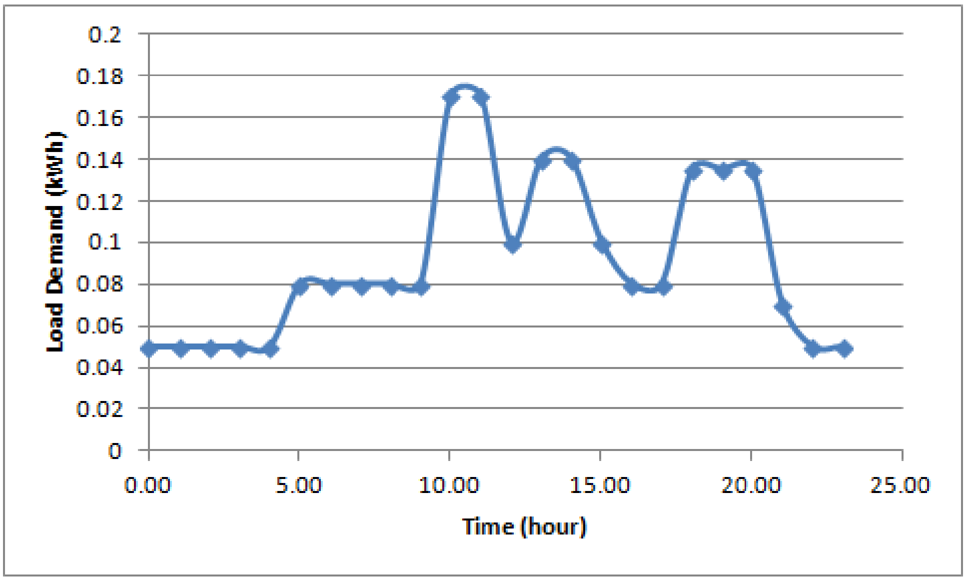

Figure 2. Hourly load profile [9, 12-15].

Table 3. Daily demands for a house of rural area [9,12-15].

Appliance	Voltage (V)	Power (W)	Daily Usage (h)	Energy (Wh)
Flourescent Lamp 1	230	20	10	200
Flourescent Lamp 2	230	40	4	160

TV	230	60	5	300
Refrigerator	230	50	24	1200
Radio Cassette	230	10	11	110
Ceiling Fan	230	60	2	120
Desk Fan	230	25	5	125
Total		265		2215

3. System design

This section consists of design process used to determine the size of SAPV components and each calculation involved in details. The analysis will be done in Amp-hour method. The advantages of Amp-hour analysis is taking account of the real world behavior of SAPV system components [16].

3.1. Estimate load demand

Design process started with estimation of total daily load requirement. First, a list of all lights and appliances, as well as loads' individual power, P_{load} and usage (in hours per day) is required. Modeling of load demand, E_{load} is calculated using equation (1). Extra amount of energy is needed to cover losses due to inefficiencies in system components. System charge requirement, Q_{load} (Ah) is calculated by equation (2), where AC losses, $_{AClosses}$ is 0.35 [9,16]. Equation (3) shows calculation of daily charge demand required, Q_{load_req}, where V_{DCbus} is DC bus voltage.

$$E_{load} = \sum P_{load} * t \quad (1)$$

$$Q_{load} = E_{load} * \left(1 + \eta_{AClosses}\right) \quad (2)$$

$$Q_{req} = \frac{E_{req}}{V_{DCbus}} \quad (3)$$

3.2. PV array selection and sizing

Before sizing the PV arrays, designers need to estimate solar energy available at the site. By selecting the month with the lowest PSH (h), PSH_{lowest}, is actually avoiding for the system to be undersize. The array sizing must match with total daily energy requirement, so by using the value obtained from equation (3), Q_{req} (Ah), system charging current from PV array, I_{charge} (A) is calculated using equation (4) [16].

$$I_{charge} = \frac{Q_{req}}{PSH_{lowest}} \quad (4)$$

The modules connection and arrangement is determined based on preselect PV model [17]. The number of parallel string, N_p is calculated using equation (5), where I_{pv_mp} is module's current maximum power under standard test condition. Next, equation (6) is used to calculate series-connected modules in each parallel string, $N_{mod/strg}$, where V_{mod_rated} is module's rated voltage. Lastly, total PV modules, N_{pv} can be calculated using equation (7) [16]:

$$N_p = roundup\left(\frac{\mathrm{I_{charge}}}{\mathrm{I_{pv\_mp}}}\right) \quad (5)$$

$$N_{mod/strg} = \frac{V_{mod\_rated}}{V_{DCbus}} \quad (6)$$

$$N_{pv} = N_p * N_{mod/strg} \quad (7)$$

3.3. Proton exchange membrane electrolyzer (PEME) sizing

The preferable/most common technologies used in water electrolyzers are Alkaline and Proton Exchange Membrane Electrolyzer (PEME). Commercially available PEME can produce from 400 to 7900 kg of hydrogen each year with pressure generation up to 13.8 bar. Meanwhile, alkaline electrolyzer produces 2400-71000 kg over a year. The advantage of PEME technology is it has high energy efficiency for each stack (75%-88%) with 5% as the minimum required output flow for a safe operation [18].

An electrolyzer decomposes water into hydrogen and oxygen by passing an electrical current (DC) between two electrode separated by an aqueous electrolyte with good ionic conductivity. The reactions take place at the anode and the cathode of electrolyzer as follows [19].

Anode: $$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \quad (8)$$

Cathode: $$2H^+ + 2e^- \rightarrow H_2 \quad (9)$$

Storage charge capacity required, Q_{storeq} is calculated based on equation (10) [16,20], where N_c is battery's reserved days, and *DOD* is battery's depth of discharge. N_c usually set as 1- 4 days, and it is advised that DOD should not be over 60%. Energy storage consumption, E_{stored} is the amount of energy consumed to produce required hydrogen, and calculated using equation (11), where η_{ely} is electrolyzer efficiency, and η_{fc} is fuel cell efficiency (η_{ely} is 0.75 and η_{fc} is 0.5).

$$Q_{storeq} = \frac{Q_{req} * N_c}{DOD} \quad (10)$$

$$E_{stored} = \frac{Q_{stpreq} * V_{DCbus}}{\eta_{ely} * \eta_{fc}} \quad (11)$$

Meanwhile, the rated power for the electrolyzer, P_{Ely} is equal to the maximum excess in the PV generation power over the minimum load power; where A_{PV} is PV panel area, and η_{PV} is PV panel efficiency [7,18].

$$P_{Ely} = H_{S\max} * A_{PV} * \eta_{PV} \quad (12)$$

3.4. H_2 storage tank sizing

Hydrogen can be stored in liquid or gas condition. Liquid hydrogen is stored in cryogenic tanks and gaseous hydrogen stored in either medium or high-pressure cylinders or near atmospheric pressure in metal hydrides.

The hydrogen formed by the electrolyzer during each month is calculated by assuming the produced hydrogen is stored completely before it supplies power to the residential load. The amount of hydrogen produced annually is the total excess of PV power transformed into volume, which is expressed in m^3 [7].

Equation (13) is the hydrogen mass produced from specific electrical energy, m_{h2} where *HHV* is higher heating values of hydrogen (33 kWh/kg). The hydrogen's required volume capacity in Normal cubic meters unit (Nm^3), V_{h2} is calculated in the next equation, where ρ_{h2} is hydrogen density and its value is 0.08988 kg/m^3 [18].

$$m_{h_2} = \frac{E_{storeq}}{HHV} \quad (13)$$

$$V_{h_2} = \frac{m_{h_2}}{\rho_{h_2}} \quad (14)$$

3.5. Proton exchange membrane fuel cell (PEMFC) sizing

The reverse reaction occurred in the electrolyzer takes place in fuel cell. Hydrogen in the anode is ionized releasing electrons and protons. Electrons flow to the cathode through a circuit producing electric current. Protons diffuse through a polymer electrolyte membrane and react at cathode with oxygen and electrons to form water. The chemical reactions happened in PEMFC are as below [19].

Anode: $$H_2 \rightarrow 2H^+ + 2e^- \quad (15)$$

Cathode: $$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (16)$$

The following equation is fuel cell sizing by considering maximum AC load power in the household, where M_{fc} is margin coefficient of the fuel cell, P_{ACload} is total power from AC load demand and η_{inv} is inverter efficiency [7].

$$P_{fc} = M_{fc} * \frac{P_{ACload}}{\eta_{inv}} \quad (17)$$

3.6. Inverter selection and sizing

Inverter is expected to deliver maximum AC load in household. Hence, inverter power rating, P_{inv} is selected using equation (18), where 1.25 is set as oversized factor [21].

$$P_{inv} = P_{ACload} * 1.25 \quad (18)$$

4. Economic analysis

Economic analysis is performed using Malaysian Ringgit, (*MYR)*. The viability of proposed system can be determined by using economic analysis. The designer will know whether the investment is feasible or not. In this paper, the life cycle cost (LCC) and levelized cost of energy (LCOE) is used to analyze system practicality. LCC is the sum of installation cost, operating and maintenance of an item for a period of time, and replacement cost in present value [22],

$$\begin{aligned} LCC = C_{pv} + C_{inv} + C_{ely} + C_{h2} + C_{fc} + \\ C_{install} + C_{cont} + C_{invrep} + C_{O\&M\_20years} - C_{salvage} \end{aligned} \quad (19)$$

where C_{pv} is PV initial array cost, C_{inv} is inverter initial cost, C_{ely} is electrolyzer initial cost, C_{h2} is hydrogen tank initial cost, C_{fc} is fuel cell initial cost, $C_{install}$ is support structure and installation cost, C_{cont} is system contingencies value (1% from initial cost), C_{invrep} is present values for inverter replacement, $C_{O\&M\_20years}$ is present worth of operation and maintenance cost for 20 year and $C_{salvage}$ is system's salvage value (20% from initial cost).

Initial price of PV panel and inverter is presented by equations (20) and (21). Initial price of electrolyzer, hydrogen storage and fuel cell is presented by equations (22)-(24). Initial price for support structure and installation cost is calculated using equation (25) and initial price's contingencies value is calculated using equation (26).

$$C_{pv} = \mathrm{Pr}ice_{pv} * N_{pv} \quad (20)$$

$$C_{inv} = \mathrm{Pr}ice_{inv} * N_{inv} \quad (21)$$

$$C_{ely} = \mathrm{Pr}ice_{ely} * P_{ely} \quad (22)$$

$$C_{h2} = \mathrm{Pr}ice_{h2} * V_{h_2} \quad (23)$$

$$C_{fc} = \mathrm{Pr}ice_{fc} * P_{fc} \quad (24)$$

$$C_{install} = \Pr ice_{install} * N_{pv} * P_{pv\_mp} \tag{25}$$

$$C_{cont} = \frac{1}{100} * C_{pv} + C_{inv} + C_{ely} + C_{h2} + C_{fc} + C_{install} \tag{26}$$

where N_{inv} is number of inverter and P_{pv_mp} module's maximum power output under standard test condition.

All components considered to have 20 years of lifetime, beside inverter (Inverter replacement is 10 years) [23,24]. C_{invrep} is calculated by equation (28), where N is component's lifetime and i is market rate. $C_{O\&M}$ is operation and maintenance cost for each year and it is predicted to be 1% from total initial cost.

$$C_{invrep} = C_{inv}\left(\frac{1}{1+i}\right)^{N} \tag{27}$$

$$C_{O\&M\_20years} = \left(C_{O\&M}\right) * \left[\frac{(1+i)^{N} - 1}{i(1+i)^{N}}\right] \tag{28}$$

Market interest rate, i is calculated using equation (29), where i' is real interest rates determined by local bank. i' is calculated as equation (30) [25]:

$$i = i' + \overline{f} - i'\,\overline{f} \tag{29}$$

$$i' = BLB - 2\% \tag{30}$$

where BLB is Base Lending Rates (Malaysia BLR is 6.60%), and $\overline{f}$ is inflation rate (Malaysia inflation rates is 2014 is 3.4%) [26,27].

LCOE (RM/kWh) is defined as the average cost per kWh of electrical energy produced by PV system [28]. It is calculated by dividing annualized life cycle cost, LCC_{1year} with total useful electrical energy generated, $E_{PV,}$ as calculated by the following equations [29]. In economic analysis calculation, market prices for the proposed system components are summarized in table 4 [8,18,24,30-33].

$$LCC_{1year} = \frac{LCC}{\left[\frac{(1+i)^{N}}{i(1+i)^{N}}\right]} \tag{31}$$

$$LCOE = \frac{LCC_{1year}}{E_{PV}} \tag{32}$$

$$E_{PV} = N_{PV} * P_{mp\_STC} * PSH_{year} * \eta_{losses} \tag{33}$$

Table 4. Components' pricing [9, 18, 24].

Components	Symbol	Unit	RM/Unit
Solar Panel	$Price_{pv}$	1	886.17
Inverter	$Price_{inv}$	1	560.71
PEME	$Price_{ely}$	RM/W	6.60
H2 Storage Tank	$Price_{h2}$	RM/Nm3	2280
PEMFC	$Price_{fc}$	RM/W	1.38
Support Structure & Installation cost	$Price_{install}$	RM/W	4.00

5. Results and analysis

This section shows the system sizing result and economic analysis for a project lifetime of 20 years.

5.1. System sizing results

Table 5 below shows technical data of each component. A combination of 1.12 kWh PV modules, 335.4 W PEME, 324.3 Nm^3 H_2 Tank, 285.0 W PEMFC, and 340 W inverter were chosen as proposed system.

Table 5. Proposed system sizing.

Daily System Energy Requirement		
Total Daily AC Energy Demand	2215.00	Wh
AC losses	775.25	Wh
Total Daily System Energy Requirement	2990.25	Wh
System Voltage	24.00	VDC
Daily System Charge Requirement	124.59	Ah
Sizing and Choosing the Modules		
Lowest Daily's Peak sun hours	4.08	h
System Design Charging Current	30.53	Amps
Details of Selected Modules		
Model	Kyocera KD140	
Type	Multicrystalline	
Peak Watts	140.00	Wp
Rated Voltage	12.00	VDC
Maximum Power Rated Current	7.91	Amps
Short Circuit Current	8.68	Amps
PV Efficiency	20.40	%
Number of Parallel String	4	
Number of Modules/ String	2	
Num of Modules	8	
PV Array Area	8.016	m^2
Hydrogen Storage Sizing and Selection		
Daily System Charge Requirement	124.59	Ah
Reserve Days	2	day
Maximum DOD	50	%
Required System Storage Capacity	498.38	Ah
Details of PEME Sizing		
Electrolyzer Efficiency, η_{elz}	75	%
Energy Storage of Electrolyzer	22653.4	Wh
Rated Power of Electrolyzer	335.41	W
Details of H_2 Tank Sizing		
Mass of Hydrogen	0.97	kg
Hydrogen Storage Capacity	10.75	Nm^3

Details of PEMFC Sizing		
Fuel Cell Efficiency, η_{fc}	50	%
Rated Power of Fuel Cell	284.95	W
Inverter Sizing and Selection		
Maximum Power AC Load	265	W
Inverter Rating	340	W
Details of Selected Inverter		
Model	Cotek SK350-224	
Rated Voltage	24/230	VDC/VAC
Rated Power	350	W
Inverter Efficiency	93	%

5.2. Economic analysis results

Table 6 below shows the economic analysis of the proposed system, as presented in previous section. Discount / interest rates value used in economic analysis is 4.60%, inflation rates value used is 3.40% and net discount rates value is 8.00%. Based on the analysis, initial cost for equipment, installation and structure is RM 39,559.79. The present value calculated for operation and maintenance is RM 3,884.06, and replacement cost is RM 259.72. The salvage value obtained for the whole system is RM 7,911.96. Hence, LCC for 20 years is RM 35,791.61, and annual LCC is RM 3,645.46. E_{PV} for the proposed system is 1828.305 kWh. Therefore, from the result, LCOE calculated is RM 1.98/kWh.

Table 6. Economic analysis.

Initial Cost		
	Components	RM
Energy Equipment	PV Module(s)	7088.48
	Electrolyzer	2213.70
	H_2 Storage Tank	24518.63
	PEMF	393.23
	Inverter	560.70
Balance of Equipment	Module Support Structure & System Installation	4480.00
Miscellaneous	Contingencies	392.55
Total Initial Cost		39647.29
O&M Cost		
	Components	RM
Annual O&M		396.48
Total Operation & Maintenance		3892.7
Replacement Cost		
Components		RM
Inverter	LCC $inverter_{n10}$	259.72
Inverter Replacement		259.72
Salvage		
Components		RM

Salvage Value	Salvage	7929.46
Result		RM
LCC Cost for 20 Years		35870.25
LCC Cost / Year		3653.47
Cost of Energy		1.98

5.3. Comparison of SAPV with AGM battery system sizing

The current results are compared with conventional sizing method and economic analysis of SAPV system with Absorbent Glass Mat (AGM) battery, which published in 2014 [9]. The finding shows that the LCC for the proposed system is RM 34,232. Meanwhile, LCC for a year is RM 3,206.82 and LCOE for the respective case is RM 1.74/kWh. Table 7 shows the comparison of current findings with previously published results.

Table 7. Economic analysis.

	SAPV with Hydrogen Storage	SAPV with AGM Battery [9]
LCC Cost for 25 Years (RM)	35791.61	34231.98
LCC Cost / Year (RM/year)	3645.46	3206.81
Cost of Energy (RM/kWh)	1.98	1.74

Based on the table, the LCC, annual LCC and LCOE for system with HSS has higher expenditure compared to the published findings. AGM battery needs to be replaced every 5 years. Meanwhile, PEME, H_2 Tank and PEMFC do not have to be replaced because the lifetime is longer, which is 20 years [24]. However, the initial cost needed for HSS is very high because fuel cell efficiency is quite low (50%). Due to that, bigger HSS capacity is needed to have back-up energy similar with AGM battery during insufficient PV generation.

6. Sensitivity analysis

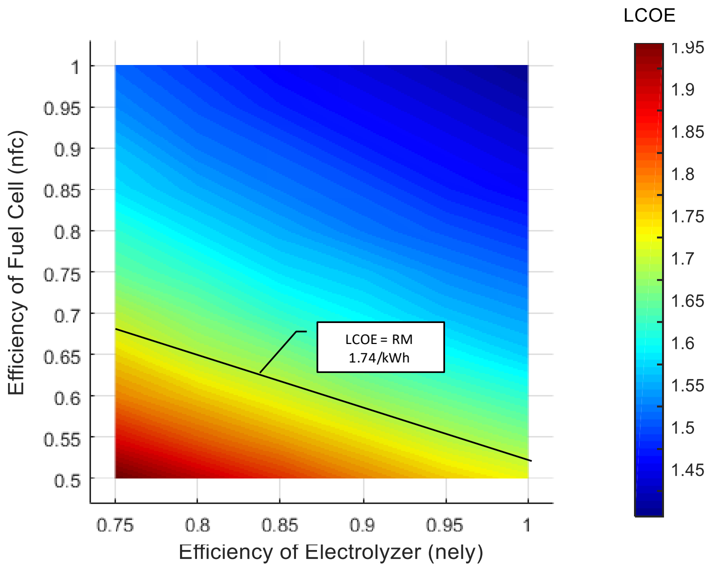

Figure 3. Effect of electrolyzer efficiency and fuel cell efficiency on levelized cost of energy.

The sensitivity of system's LCOE will be affected by η_{elz} and η_{fc}. In the future, enhancing η_{elz} and η_{fc} is crucial to ensure SAPV with HS can compete with conventional SAPV with AGM Battery system. A benchmark value of η_{elz} and η_{fc} to acquire LCOE equal or lower than conventional system will be obtained from this analysis. A range of 0.75 - 1.00 is considered for η_{elz} and a range of 0.50 - 1.00 is for η_{fc}. The effect of η_{elz} and η_{fc} on LCOE is shown in figure 3 above.

Based on figure 3, for a specific LCOE value (eg: RM1.74 kWh), the relation between η_{elz} and η_{fc} is approximately linear. Hence, the result can be simplified by using relationship between product of η_{elz} and η_{fc} ($\eta_{elz}*\eta_{fc}$) and LCOE, as represented in figure 4. From figure 4, it shows that in order to obtain an LCOE lower than SAPV with AGM battery, $\eta_{elz}*\eta_{fc}$ has to be higher than 0.52.

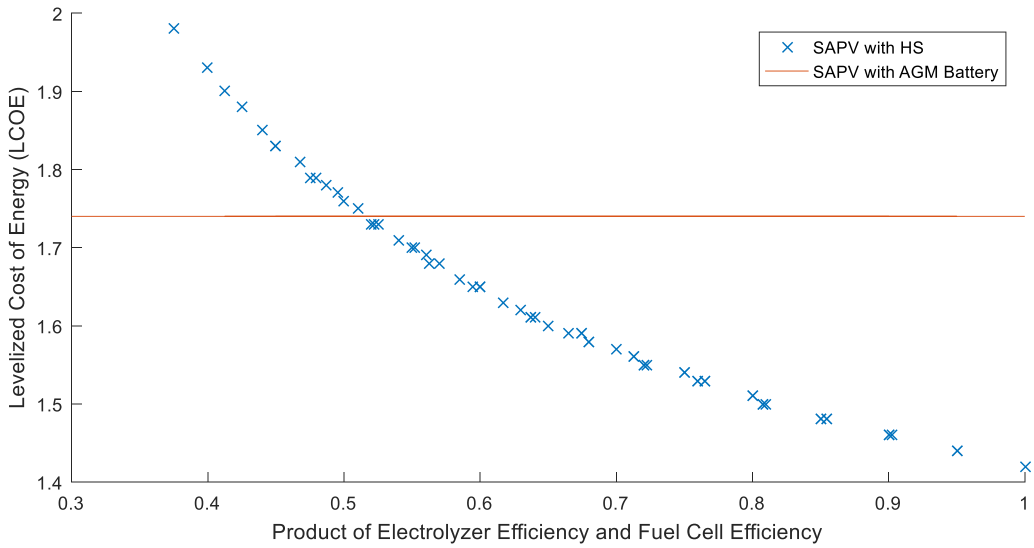

Figure 4. Effect of $\eta_{elz}*\eta_{fc}$ on levelized cost of energy.

7. Validation of electrolyzer and fuel cell efficiencies

Validation of efficiency for PEME and PEMFC available in current market is performed and analyzed in this section. Electrical efficiency of electrolyzer, η_{ely} is verified by experimental setup and the result is shown in the figure below. By using constant input voltage and current on electrolyzer (1.81VDC and 1.11ADC), time required to produce each 5 cm^3 of hydrogen is measured, as illustrated in figure 5. η_{elz} is calculated as equation (34), where the η_{ely} actual value obtained was 75.8%, which is within range claimed by previous reference and validated the value use in this analysis (0.75) [11].

$$\eta_{ely} = \frac{E_{hydrogen}}{E_{electrical}} = \frac{V_{H_2} * LHV}{V*I*t} = \frac{0.00003cm^3 * 9.9*10^6\ J/m^3}{1.81V*1.11A*195s} = 0.758 = 75.8\% \tag{34}$$

PEMFC efficiency was also calculated based on results obtained from experiment. To obtain constant output voltage and current from fuel cell (2.87VDC and 0.337ADC), time required to consume each 5 cm^3 of hydrogen is measured, as illustrated in figure 6. η_{fc} is calculated as equation (35) below. Unfortunately, η_{fc} actual value obtained was 43.8%, which is lower than efficiency value used in this sizing method (0.5). Hence, it is advised to make additional review in the future to search for better fuel cell with higher efficiency value in order to obtain more reliable system.

$$\eta_{fc} = \frac{E_{electrical}}{E_{hydrogen}} = \frac{V*I*t}{V_{H_2} * LHV} = \frac{2.87V*0.337A*112s}{0.000025cm^3 * 9.9*10^6\ J/m^3} = 0.438 = 43.8\% \tag{35}$$

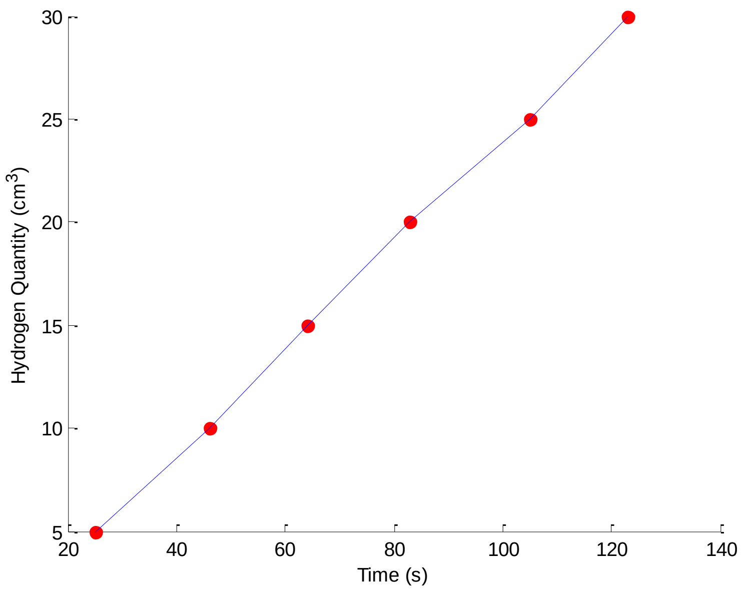

Figure 5. Volume of hydrogen's produced from PEME vs time diagram.

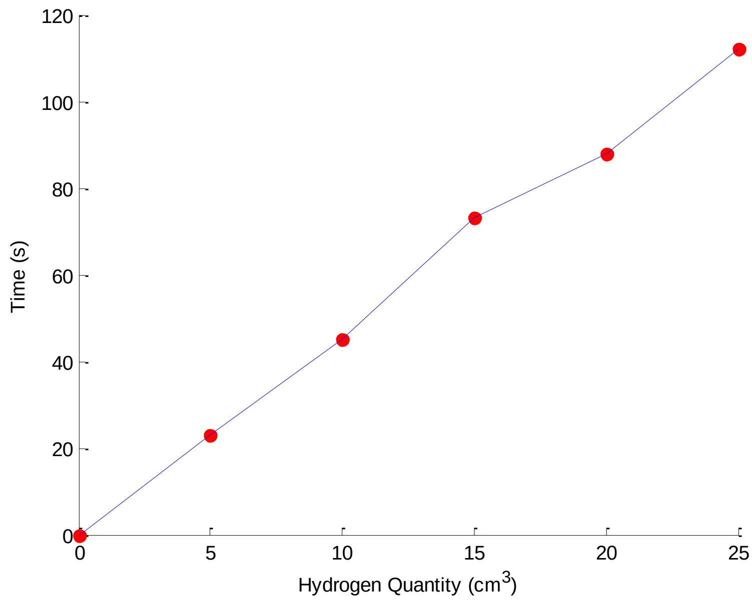

Figure 6. Hydrogen consumption of PEMFC vs time vs power produced.

8. Conclusion
Sizing and economic analysis of SAPV with HSS has been presented. A small scale household demand and daily's average solar irradiation was used to design off-grid PV system. Economic assessment is employed to calculate the life cycle cost and levelized cost of energy analysis. It shows the LCC for proposed system is RM 35,791.61. Meanwhile, annual LCC is RM 3,645.46 and LCOE value obtained is RM 1.98 kWh.

However, compared to economic analysis of SAPV with AGM batteries from the previously published results [9], the expenditure for SAPV with AGM battery is lower, where LCC for the system is RM 34,232, annual LCC is RM 3,206.82 and the LCOE for the respective cases is RM 1.76/kWh. Based on current findings, even though hydrogen energy storage has high energy density per mass, the system has low efficiency as a storage system and still expensive. Due to the low efficiency storage, designers need to allocate hydrogen storage capacity higher than AGM battery. However, as an emerging commercialize product, the manufacturers and researchers can focus on how to increase storage system efficiency for the future usage. The HSS round-up trip must improve dramatically before they can offer the same overall energy efficiency as batteries.

Therefore, a sensitivity analysis is performed to find a benchmark value of electrolyzer and fuel cell efficiencies to acquire acceptable levelized cost of energy. From the analysis, in order to obtain an LCOE lower than SAPV with AGM battery, $\eta_{elz}*\eta_{fc}$ has to be higher than 0.52. Besides, the electrolyser efficiency and fuel cell in current market are validated using laboratory's experimental data. This finding is needed to envisage the applicability of photovoltaic system with hydrogen storage as a future power supply source in Malaysia.

Acknowledgments
The authors wish to acknowledge the supports for this research paper received from Malaysian Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia leading to this article under the Tier 1 grant (vote no: Q.J130000.2523.14H02).

References

[1] Mellit A and Kalogirou S A 2008 Artificial intelligence techniques for photovoltaic applications: A review *Progress in Energy and Combustion Science* **34** 574-632
[2] Castañeda M, Cano A, Jurado F, Sánchez H and Fernández L M 2013 Sizing optimization, dynamic modeling and energy management strategies of a stand-alone PV/hydrogen/battery-based hybrid system *International Journal of Hydrogen Energy* **38** 3830-45
[3] Pellow M A, Emmott C J, Barnhart C J and Benson S M 2015 Hydrogen or batteries for grid storage? A net energy analysis *Energy & Environmental Science* **8** 1938-52
[4] Mustapa S I, Peng L Y and Hashim A H 2010 Issues and challenges of renewable energy development: A Malaysian experience *Energy and Sustainable Development: Issues and Strategies (ESD), 2010 Proceedings of the international conference on* 1-6
[5] Zhou W, Lou C, Li Z, Lu L and Yang H 2010 Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems *Applied Energy* **87** 380-9
[6] Elbaset A A 2011 Design, modeling and control strategy of PV/FC hybrid power system *J. Electrical Systems* **7** 270-86
[7] Jallouli R and Krichen L 2012 Sizing, techno-economic and generation management analysis of a stand alone photovoltaic power unit including storage devices *Energy* **40** 196-209
[8] Barsoum N and Vacent P 2007 Balancing cost, operation and performance in integrated hydrogen hybrid energy system *First Asia International Conference on Modelling & Simulation* 14-8
[9] Nordin N D and Rahman H A 2014 Design and economic analysis in stand alone photovoltaic system *2014 IEEE Conference on Energy Conversion (CENCON)* 152-7
[10] King D L, Boyson W E and Kratochvil J A 2002 Analysis of factors influencing the annual energy production of photovoltaic systems *Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE* 1356-61
[11] 23rd February *PVsyst: Software for Photovoltaic System*. Available: http://www.pvsyst.com/en/
[12] Shen W 2009 Optimally sizing of solar array and battery in a standalone photovoltaic system in Malaysia *Renewable Energy* **34** 348-52
[13] Nordin N D and Rahman H A 2016 A novel optimization method for designing stand alone photovoltaic system *Renewable Energy* **89** 706-15
[14] Nordin N D and Rahman H A 2015 An optimization method for designing stand alone photovoltaic system using iterative method *2015 IEEE International Conference on Smart Energy Grid Engineering (SEGE)* 1-6
[15] Nordin N and Rahman H A Assessment of conventional and improved SAPV sizing methods using statistical indicator

[16] M. Hankins, *Stand-alone Solar Electric Systems: The Earthscan Expert Handbook for Planning, Design and Installation*: Earthscan, 2010.
[17] (20 May 2014). *PV Modules in a String*. Available: https://nationalvetcontent.edu.au/alfresco/d/d/workspace/SpacesStore/4e1e0e97-bc55-4c44-a692-4d31f4d0d934/13_02/content_sections/learn_about/08_solar_page_010.htm
[18] H. Tebibel and S. Labed, "Design and sizing of stand-alone photovoltaic hydrogen system for HCNG production," *International Journal of Hydrogen Energy,* vol. 39, pp. 3625-3636, 2014.
[19] Ipsakis D, Voutetakis S, Seferlis P, Stergiopoulos F and Elmasides C 2009 Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage *International Journal of Hydrogen Energy* **34** 7081-95
[20] Nafeh A 2009 Design and economic analysis of a stand-alone PV system to electrify a remote area household in Egypt *Open Renewable Energy Journal* **2** 33-7
[21] Sulaiman S I, Rahman T K A, Musirin I and Shaari S 2011 Sizing grid-connected photovoltaic system using genetic algorithm, *2011 IEEE Symposium on Industrial Electronics and Applications (ISIEA)* 505-9
[22] Applasamy V 2011 Cost evaluation of a stand-alone residential photovoltaic power system in Malaysia *2011 IEEE Symposium on Business, Engineering and Industrial Applications (ISBEIA)* 214-8
[23] Sullivan W G, Wicks E M and Luxhoj J T 2009 *Engineering economy*: Pearson Prentice Hall
[24] Zoulias E and Lymberopoulos N 2007 Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems *Renewable Energy* **32** 680-96
[25] Park C S, Kumar P and Kumar N 2004 *Fundamentals of engineering economics*: Pearson/Prentice Hall
[26] 1 December 2014 *Bank lending rates* Available: http://www.blr.my/
[27] 2017 August *Malaysia inflation rates* Available: http://www.tradingeconomics.com /malaysia/inflation-cpi
[28] Kamel S and Dahl C 2005 The economics of hybrid power systems for sustainable desert agriculture in Egypt *Energy* **30** 1271-81
[29] Näsvall D 2013 Development of a model for physical and economical optimization of distributed PV systems
[30] 20 May 2014 *Sealed-AGM batteries* Available: http://www.wholesalesolar.com /products.folder/battery-folder/Surretterolls.html#SealedAGMBatteries
[31] 20 May 2014 *140 Watt black frame solar panel* Available: http://www.ecodirect.com/Kyocera-KD140GX-LFBS-140-Watt-PV-Panel-p/kyocera-kd140gx-lfbs.htm
[32] 20 May 2014 *Blue sky energy* Available: http://www.blueskyenergyinc.com/pricing/
[33] 20 May 2014 *350 Watt 24 volt inverter / pure sine wave* Available: http://www.ecodirect.com/Cotek-SK350-124-350W-24V-Pure-Sine-Inverter-p/cotek-sk350-124.htm