Optimal Design of PV-Fuel Cell Hybrid Power System for Rural Electrification

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Abstract: *This paper is design and developments of a standalone solar photovoltaic-fuel cell (PV-FC) hybrid power generation system for remote areas. A solar panel is designed in Matlab/Simulink, and Proton Exchange Membrabe (PEM) fuel cell stack and Lithium-ion battery are also designed. In this paper, a proposed area, Bodawtaw village at Shwebo District in Myanmar where there is no access the electricity from national grid is chosen and the renewable energy potential for this region is evaluated to make the system sizing and design of stand-alone photovoltaic (PV)-fuel cell hybrid system. In this research work, the total installed capacity of the proposed hybrid system is studied for 82 kW which contributes 129kW of PV generator and 2 stacks of 50kW PEM fuel cell system. The proposed system can meet the load for every hour of the days without interruption. The results show that the average daily load requirement and available solar power for three seasons. PV system supply the load at an average of 6-9 hours in day time and remaining time load is supplied by fuel cell and battery bank.*

Key Words: *Solar Photovoltaic (PV), Fuel Cell (FC), Proton Exchange Membrane Fuel Cell (PEMFC), Hybrid System, Remote area*

1. INTRODUCTION :

Global environmental concerns, increasing energy demands and developments in renewable energy technologies present a new possibility to implement renewable energy sources. Solar energy is the most prominent among renewable sources, as it is an inexhaustible resource and its exploitation has thus far been ecologically friendly. The potential amount of PV energy is considerably greater than current worldwide energy demands. So, PV energy has been developing more rapidly than the other renewable energy sources for the last few decades. However, only using the renewable energy systems cannot be reliable in itself without using the back-up system like engine generators or energy storage devices like batteries. Therefore, hybrid energy system that combines more than one renewable energy technology with back-up system may be obtained by combining various kinds of resources, using diesel-, fuel cell-, biomass-, wind-, PV-, or small hydro-generators. In recent times, fuel cell technology also has experienced a rapid growth and it shows great potential to be green energy source in near future because of its unique features (low emission of pollutants, fuel flexibility, and modular structure).

The problem statement of this research is that the load centre of non-electrified villages is located far away from the substation and the national grid. Therefore, these areas cannot access the electricity until now The need of reasonable and reliable electricity is very much necessary to develop remote rural areas in developing countries [5]. In these regions, electric power is provided by various options. One is for extending the transmission network of existing system, and receiving power from a distant location. However this is not possible to use practice because of high price transportation lines, their losses, and stability issue that may occur during long range power transmission [1].

Therefore, renewable energy system can be a favourable solution due to its less installation, operation, and maintenance costs. According to the rural electrification organization, one of the most appropriate and environmentally friendly solutions to supply electricity to those areas is photovoltaic (PV) generation. In case of solar. Its output depends on the solar irradiation, operating temperature.

Since solar irradiation varies from time to time, PV output is not continuous and this intermittency can be avoid by integrating solar with other alternative energy sources. Therefore, integrating fuel cell with PV is the effective solution to increase the reliability as well as efficiency. A hybrid system composed with PV, fuel cell, and battery energy storage system has been suggested to meet the demand reliably at an islanded rural area. The main objective when designing such system is to construct the model and simulate the proposed system for supplying the power reliably.

Myanmar is a country with a lot of renewable energy resources and non-electrified rural villages, which accord with the necessary conditions of the standalone system. The proposed area in this dissertation is the Bodawtaw village, which is located at 22.579^0 (N) Latitude and 95.698^0 (E) Longitude at Shwebo District in Sagaing Region in Myanmar The problem statement of this research is that the load center of proposed village cannot access the electricity until now. Furthermore, the climatic data for PV energy has been found through NASA's website [6]. The average solar radiation for this area is observed as 4.841kWh/m2/day [6].

2. STAND ALONE PV-FUEL CELL HYBRID SYSTEM :

To design a standalone PV-FC system, several components are needed to perform the power generation and conversion function. The power ratings or size of the systems are determined from the load profile. The configuration of the components in the PV-FC hybrid system is shown in Fig. 1.

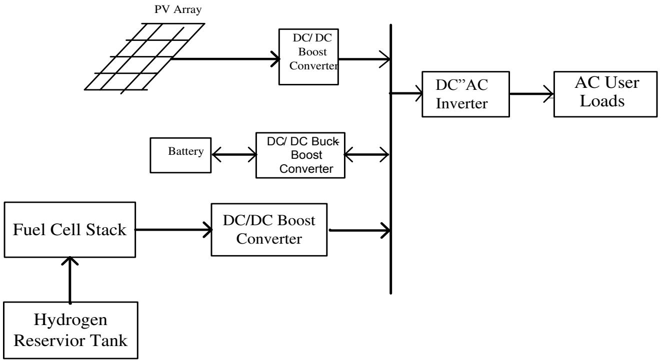

Fig. 1. System Configuration of the Proposed Hybrid Energy System

In a solar PV based hybrid renewable energy system, PV is the primary sources of energy supply the load. Excess energy from PV is primarily stored in the battery bank, when the battery state of charge (SOC) reaches the maximum limit. Absence of PV power causes the battery SOC reaches a minimum limit the deficit power is met by starting the fuel cell which operates by consuming the stored H_2. Thus, the combination of PV, fuel cell and battery serves as an ideal option to power stand-alone loads.

2.1 . Solar PV System Design

Solar energy is a good choice for electric power generation and electromagnetic radiation of solar energy directly converted into electrical energy. Solar cell is basically a p-n junction fabricated in a layer of semiconductor. It can be modelled with one diode equivalent circuit as shown in Fig. 2 [8].

Solar cells are connected in series and parallel combination to achieve the required power rating and Maximum Power Point Tracking (MPPT) system is designed to extract the maximum power available from the panel. MPPT is an electronic DC-DC converter which optimizes the matches between solar panel and battery bank or grid.

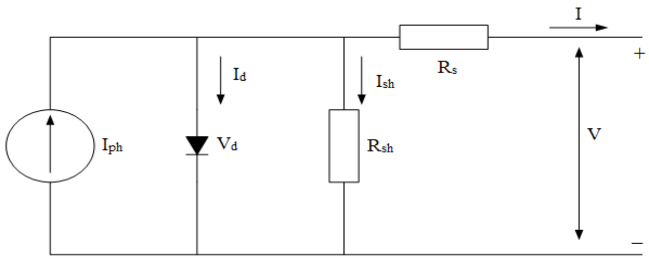

Fig. 2. Equivalent circuit of PV cell [1]

The mathematical model of the voltage-current characteristic equation of a solar cell is expressed as follow:

$$I = I_{ph} - I_s\left(\exp\frac{(V + IR_s)}{(nV_t CN_s)} - 1\right) - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

Where, C is the number of cells in a PV panel, N_s & N_p is the number of PV panel in series & parallel, I_{ph} is the photocurrent, I_s is the cell saturation current, R_{sh} is the shunt resistance, R_s is the series resistance.

2.2. PEM Fuel Cell System Design

Fuel cell is defined as an electrochemical device that continuously converts the chemical energy of a fuel and oxidant into electrical energy and heat as long as the fuel and oxidant are supplied to the electrodes. Among different types of fuel cells available, the Proton Exchange Membrane FC (PEMFC) has drawn the most applications due to its simplicity, quick start up, higher power density, and operation at lower temperatures. The operation of fuel cell is explained by Fig. 3.

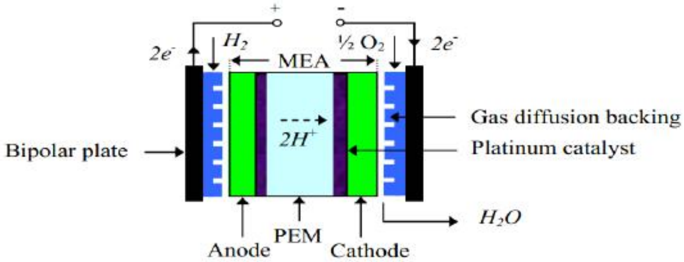

Fig. 3. Basic-description of fuel cell operation [8]

In a typical fuel cell, fuel is fed continuously to the anode and an oxidant. The electrochemical reactions take place at the electrodes as fuel and oxidant are supplied, producing electrons. Electrons are produced at the anode and are consumed at the cathode. Electrons move from anode to cathode via an external circuit. As a result this movement of electrons produces electricity [8]-[9].

The equations governing the operation of a PEM FC are

At the anode; $2H_2 \rightarrow 4H^+ + 4e^-$ (2)

At the cathode; $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ (3)

As the output magnitude of the fuel cell stack is high, DC-DC boost converter is designed to increase the stack voltage up to bus voltage level.

2.3. Battery Storage System

Batteries can be used for two independent purposes storage of energy and as a power conditioning mechanism. Battery bank is integrated with the solar PV and fuel cell system to overcome the intermittency and lithium-ion batteries are the most viable solution among the available batteries because of their robustness and lower cost per kWh.

3. DESIGN MANAGEMENT FOR PROPOSED VILLAGE :

The case study is considered for supplying electricity to Bodawtaw village which is located at 22.579^0 (N) Latitude and 95.698^0 (E) Longitude at Shwebo District in Sagaing Region in Myanmar [6] as a mentioned in introduction. There are about 350 house-holds with 1800 of local people in this village.

Table I is describes the total daily load demand for residence and communal facilities in kWh. The proposed area in this dissertation is the Bodawtaw village. The problem statement of this research is that the load center of proposed village cannot access the electricity until now. The electrical loads include Lighting, medium size refrigerator, pump, computer and other ordinary household electrical appliances, e.g. TV sets, electric fan, phone charger etc. Loads are divided into two groups, that is, residence and communal facilities. The residence consists of 350 households in, low, medium and high income levels. The communal facilities include school, monastery, rural health clinic and street lighting. The parallel hybrid energy system is intended to apply for 350 households residing at the selected site [5]. The daily load comsumotion of the proposed area is shown in Fig. 4.

Table I. Load Components in Proposed Village

Components		**Numbers**	**Power consumption (kWh/day)**
Residence	Low income	200	154
	Medium income	100	147
	High income	50	199
Communal facilities	School	1	5.34
	Monastery	1	4.03
	Rural Health Clinic	1	5.34
	Street lighting	200	18
Total power consumption per day			532.64

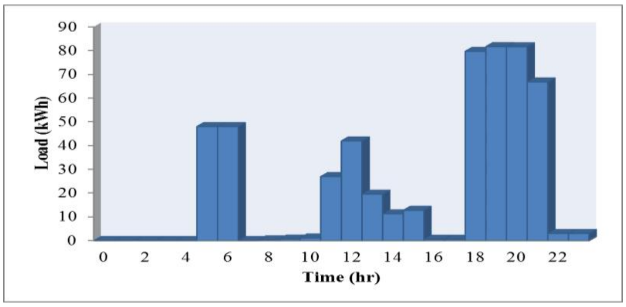

Fig . 4. Daily load profile of the proposed area

4. SUPPLY SIDE MANAGEMENT for Proposed Village:

The supply side management will focus on the system reliability of the proposed hybrid system. The specific monthly solar radiation profile for the selected village is shown in Fig. 5. The highest and lowest solar radiation occurs in April and September, respectively. In April, the PV array can satisfy the whole load during the daytime and to meet the load in the evening and night with the energy stored in the battery energy storage systems.

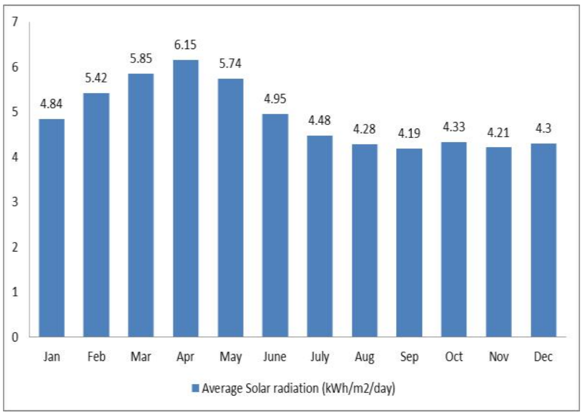

Fig. 5. Monthly Solar Radiation Profile

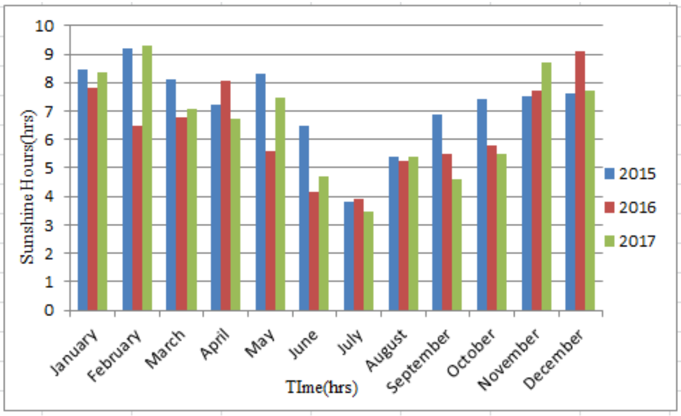

Fig.6. Peak Sun hours (hrs./day) of the Proposed Village

Table II. Available Sunshine Hours of Proposed Village in Yearly

Month	2015	2016	2017
January	8.47	7.8	8.37
February	9.2	6.5	9.3
March	8.1	6.8	7.05
April	7.2	8.04	6.74
May	8.3	5.6	7.47
June	6.5	4.15	4.7
July	3.8	3.93	3.47
August	5.41	5.23	5.4
September	6.9	5.5	4.6
October	7.4	5.8	5.5
November	7.5	7.7	8.7
December	7.6	9.1	7.73

Table II is described the average number of sunshine hours of the proposed village for each month from 2015 and 2017. It is clear from Fig. 6 that more available sunshine hour in summer. The average number of sunshine hours is 7.525hrs/day in summer, 4.9hrs/day in rainy season and 7.4hrs/day in winter. For instance, the variation of solar irradiance in day time in summer (February to May), rainy (June to September) and winter (October to January) of proposed village is as shown in Fig. 7. Fig. 8 shows the PV array output power in three seasons.

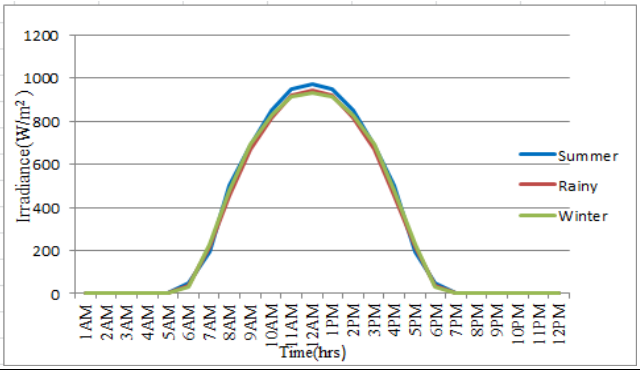

Fig.7. Variation of Solar Insolation in Bodawtaw village

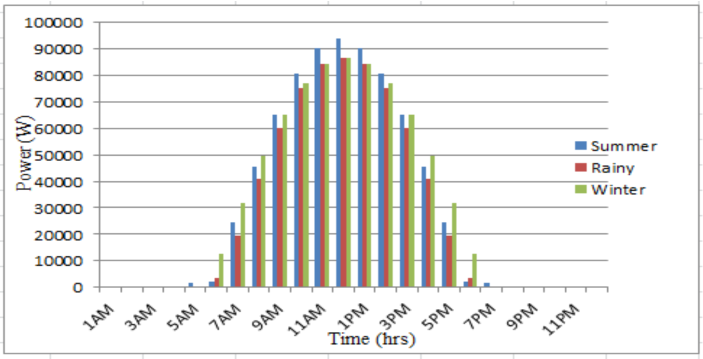

Fig. 8. PV array Output Power in Three Seasons

5. DESIGN CALCULATION FOR STAND-ALONE SYSTEM

In the proposed area, off-grid PV-FC with battery backup system is installed. This section describes the equations to calculate the sizing of PV array, the sizing of fuel cell stack and the size of the battery bank.

5.1. Determining the Sizing of PV Array

The system array size calculation is as follow:

Total daily energy demand, E_d=532.64kWh/day

The required daily average energy demand, $E_{rd} = \dfrac{E_d}{\eta_{bat}\eta_{inv}\eta_c}$ (4)

The average peak power, $P_{ave,peak} = \dfrac{E_{rd}}{T_{sh}}$ kW/day (5)

The total dc current of the system, $I_{dc} = \dfrac{P_{peak}}{V_{dc}}$ (6)

The total number of module, $N_{total} = \dfrac{\text{Peak Power}}{\text{Power for one module}}$ (7)

Number of modules in series, $N_s = \dfrac{\text{Voltage of DC PV Generator}}{\text{Voltage of one module}}$ (8)

Number of modules in parallel, $N_p = \dfrac{\text{the total dc current of the system}}{\text{the rated current of each module}}$ (9)

The total number of module, $N_{total} = N_s \times N_p$ (10)

There are 310 numbers of poly crystalline PV modules in this system. The array composed of 62 parallel strings with each containing 5 modules in series to obtain a terminal voltage suitable for the purpose system.

The electrical characteristic of the photovoltaic Mitsubishi electric Sun Power SPR-415E-WHT-D PV Panel Module specification chosen is described in Table III. The entire stand-alone PV system was designed in MATLAB/Simulink software. The radiation is kept constant at 1000 w/m2 in this simulation.

5.2. Determining the Sizing of Battery Bank

System battery size can be calculated by using the following Equations. The required daily average energy demand has already been calculated in Equation (4). The selected storage days should be 2 days at least because Bodawtaw village is located at center of Myanmar and it has good solar radiation. Maximum depth of discharge is based on the selected battery and it is 80 percent of Lithium-ion battery.

The estimate energy storage, E_{est} = Erd × the number of autonomy days (11)

The safe energy storage, $E_{safe} = \dfrac{\text{the estimate energy storage, } E_{sd}}{\text{maximum depth of discharge, } D_{dish}}$ (12)

The total capacity of battery bank in ampere-hours, $C_{tb} = \dfrac{\text{the safe energy storage, } E_{safe}}{\text{the rated dc voltage of one battery, } V_b}$ (13)

And then number of parallel batteries and series batteries will be calculated as follow:

The total number of batteries, $N_{tb} = \dfrac{C_{tb}}{C_b}$ (14)

The number of batteries in series, $N_{sb} = \frac{V_{dc}}{V_b}$ (15)

The number of parallel batteries, $N_{pb} = \frac{N_{tb}}{N_{sb}}$ (16)

Therefore, the required battery capacity is 76344.479 Ah. The suitable design with system is Lithium-ion battery model. Its capacity is 600 A, 24 V and 80 percent discharging. There are 135 numbers of batteries in this system which composed of 9 parallel strings with each including 15 batteries in series. The battery is modeled as a nonlinear voltage source whose output voltage depends not only on the current but also on the battery state of charge (SOC), which is a nonlinear function of the current and time.

5.3. Determining the Sizing of PEM Fuel Cell

According to Faraday's law, the consumption rates of hydrogen in a fuel cell is directly proportional to the transfer rate of electrons to the electrodes, which in turn is equivalent to the electrical current in the external circuit[8]. Hence, the total consumption rate of hydrogen in a fuel cell, which consists of several cells connected in series, can be expressed as:

$$\dot{m}_{H2,C} = N_{cells} \times \frac{I_{fuel\,cell}}{n.F} \quad (20)$$

The required number of PEM fuel cells and number of stacks can be derived as:

$$N_s = \frac{\text{PEM FC System Voltage}}{\text{PEM FC Stack Voltage}} \quad (21)$$

$$N_p = \frac{\text{PEM FC System Power}}{\text{PEM FC Stack Power}} \quad (22)$$

Table III. Design Parameters of PV-FC Hybrid System

Technical Parameters	Value
Photovoltaic model Number of cells per module	128
Maximum Power (P_{max})	415W
Rated voltage (V_{mp})	72.9 V
Rated current (I_{mp})	5.69A
Open-circuit voltage (V_{oc})	85.3V
Short-circuit current (I_{sc})	86.09A
Series resistence (R_s)	0.5371 Ω
Shunt resistence (R_p)	419.7813Ω
Diode ideal factor	0.87223
Number of parallel modules, N_p	62
Number of series modules, N_s	5
Total number of modules, N_{total}	310
Array rated current	352.78 A
Array rated voltage	364.5 V
PEM Fuel Cell System Stack power	50kW
Number of cell	900
Nominal operating voltage	625 v
Nominal operating current	80 A
Operating temperature	65°C
Nominal stack efficiency	50%
Number of parallel stacks, N_p	2
Number of series stacks, N_s	1
Total number of modules, N_{total}	2
Lithium-ion Battery System Rated Voltage	360 v
Rated capacity	4071.68Ah
Initial SOC	50%
Battery response time	20 sec
Cut-off voltage	270 v
Fully charged voltage	380A
Required battery capacity	76345 Ah
Number of paralleled batteries, N_p	9
Number of series batteries, N_s	15
Total number of batteries, N_{total}	135

In the proposed system, the two stack of 50kW PEM fuel cell is connected in series and the number of 900 cells, which successfully covered the excess demand. Table III is described design parameters of the proposed hybrid system.

In this research work, the total installed capacity of the proposed hybrid system is studied for 82 kW which contributes 129kW of PV generator and 2 stacks of 50kW PEM fuel cell system. The proposed system can meet the load for every hour of the days without interruption. The results show that the average daily load requirement and available solar power for three seasons. In order to meet this load demand, an array of 310 solar panels is required.

Fig. 9 is shown as the PV array output power and the load consumption power for proposed village. In contrast to Fig.7, from 00:00 to 5:00, the PV array output power is zero, at the same time solar radiation is zero; from 6:00 to 19:00, when the PV array output power increased after the first drop, which is consistent with the solar radiation.

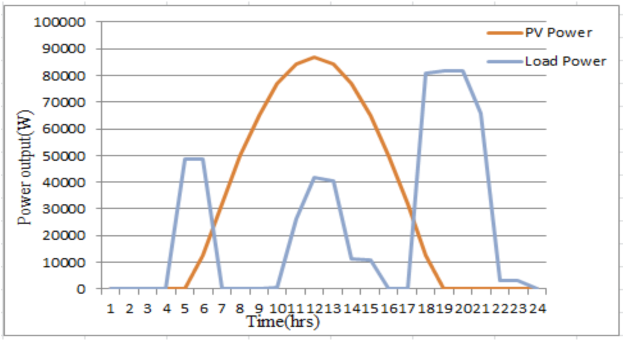

Fig . 9. PV Power and Daily Load for the Proposed Village

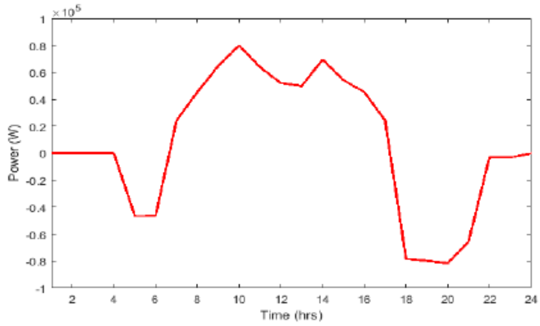

Fig. 10. Difference of PV Power and Load Power

Regarding to Fig. 10 which depicts the difference between power of solar cell and load power, the places of curves which are in negative section are showing the discharged of battery bank, and in positive section is charging the battery state of charge.

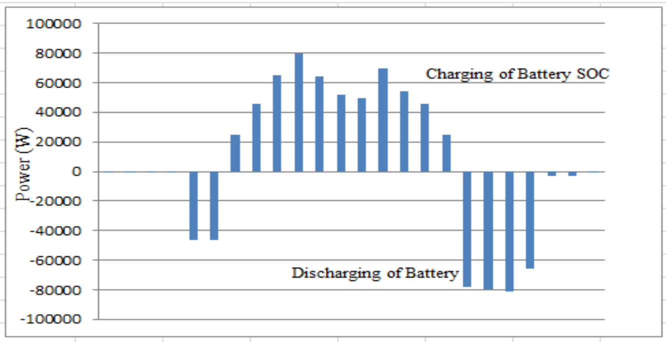

Fig.11. Charging and Discharging Power of Battery

Fig. 11 shows the charging and discharging power of battery state of charge. During the day time, the PV system supplies the load and excess energy from PV is also stored in the battery bank. During night time, battery storage system is employed to meet the night load. In cloudy days, since the PV output power is low in the daytime, battery storage becomes insufficient. Therefore, the fuel cell is operated by consuming the stored H_2 tank. Thus, the combination of PV, fuel cell and battery serves as an ideal option to power standalone loads.

6. CONCLUSION:

In this paper, a selected village in Myanmar is designed the economic feasibility of a standalone system considering the specific local conditions and resource availability for the village. In this paper is studied of the optimal design of a hybrid photovoltaic -fuel cell generation system and battery energy storage which is designed consideration. The results showed that the hybrid system with both PV and FC was able to decrease power shortage and greenhouse gas emissions while maintaining the reliability. Moreover, the addition of battery energy storage improved the benefits in terms of cost and environmental effects by managing the variations in the PV generation. The system is applicable for remote areas or isolated loads.

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