A Hybrid Solar PV system with islanded operation capability for Critical Loads

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***Abstract*— Design, simulation, and optimization of a Hybrid Solar PV system with the capability of achieving islanded operation mode was investigated in this study. The main objective of the project was to propose a Hybrid Solar PV system to a commercial load that could be utilized as a backup power system in the event of a power outage, as an alternative to fossil fuel-fired backup power sources. This study focuses on proposing a Hybrid Solar PV system for the University Hospital of Kotelawala Defence University, to meet the demand during a power outage with the integration of Solar PV generation to reduce expenses on the conventional usage of fossil fuel as an auxiliary energy source and reduce carbon footprint by implication. The architecture of the power system was designed to incorporate a Battery Energy Storage System (BESS) with a rooftop Solar Plant to an already existing diesel generator (DG), that can operate in both off-grid and grid-connected modes. The study investigates the most feasible and economical methods to supply the load during an outage. An analysis of energy economics utilizing Levelized Cost of Energy (LCOE) concludes that the Hybrid Solar PV system with a Li-ion BESS is more viable than using a DG to meet the load during islanded operation. The capability to perform peak shaving on normal days, export excess solar generation, and minimalized fuel costs impart high monetary benefits over the expected lifetime of the microgrid. A simulation of the model using MATLAB Simulink and a techno-economic analysis using the HOMER Pro software was performed to investigate the performance and reliability of the design and to conclude upon characteristics of the optimum configuration of the proposed microgrid.**

Keywords - Hybrid Solar PV system; BESS; Islanded operation; Microgrids; Optimization; Simulation

I. INTRODUCTION

A microgrid is an independent power system that uses various sources of energy along with energy storage systems and power control units to supply a given demand. Microgrids can be divided into three types according to the types of connection: Grid-tied systems, Standalone system, and Hybrid Systems. Hybrid systems can switch from islanded mode (off-grid) to grid-connected mode (on-grid) and increase the performance while reducing disruptions brought on by intermittent nature of renewable energy.

The purpose of a standalone PV system is to independently generate power and supply to predetermined loads. When the load exceeds the generation while the system is in the islanded mode, load shedding is carried out. Critical loads, however, should get a constant supply of power. According to the analysis in the paper [1], in such situations, a pump storage station can be used to maintain the essential loads. To satisfy the residential loads in Dhaka city, a PV-diesel hybrid power system with battery storage was created to minimize the use of the available Diesel generators [2]. Despite the fact that research from [3]– [4] demonstrate a variety of advantages of installing a standalone PV system, they have drawbacks such as high installation cost and a limited energy storage capacity Batteries can be used to supply power if the PV generation is insufficient in the islanded mode.

Battery storage is commonly used in many standalone microgrids to store generated energy and supply during periods of low generation & by implication reduce the carbon footprint. A Hybrid Solar PV-Fuel Cell power system was proposed to supply power for a residential community with 150 houses in a study. The proposed system in this paper offered good penetration of renewable energy sources (renewable fraction f_{ren}=40.2%), low cost of energy, low excess power (18%), and produced zero carbon dioxide emissions during the generation of energy [5]. Batteries are used to enhance the reliability of grid-connected microgrids. The study in [6] proposes a system with a hybrid PV-battery system to supply the loads during a blackout. The paper studies the benefits of applying economic model predictive control to optimize this system. As an economical alternative, batteries can also be used to meet the peak demand. A study was done for a residential community in South Africa where a grid-connected Hybrid Solar PV-battery system was proposed to supply the demand from Solar PV power and battery storage during sun peak hours and peak shave during peak demand [7]. In microgrids with the islanded operation, variations of power due to intermittent nature of renewable energy, result in changes in the frequency and voltage stability of the system. Installed generators can be used to negate the fast changes in power output. But this may result in wear and tear of the governor system of the generator in the long run. As a result, many studies have been done to explore BESS to mitigate the inherent intermittencies of Solar power on the grid [8]- [9]. Several studies have proposed Hybrid energy Storage systems with Solar PV to mitigate Solar power fluctuations [10]. In the paper [11] the authors propose a super capacitor bank with Vanadium Red-Oxide Battery as BESS to smooth the solar output power. Power outages may occur as a result of unexpected grid disturbances or demand management (Load Shedding) performed by the utility.

Power outages have a significant negative impact on critical loads that require a constant supply of electricity. Therefore, it is vital to install a system that could provide continuity during such circumstances. Most of the Sri Lankan commercial entities rely on diesel generators to meet their energy needs during power outages. The usage of diesel generators has significant environmental repercussions, including global warming and greenhouse gas emissions. The overall aim of this study is to design, model, simulate, and control a Hybrid Solar PV Power System with islanded operation capability for identified critical loads, along with performing useful energy economic calculations comparison between lithium-ion battery storage against diesel generator is done.to optimize the usage of various sources of energy.

II. LOAD IDENTIFICATION

The critical load is specified by the power consumption of University Hospital of KDU. The average daily energy consumption is 33468.95 kWh/day. The monthly average power consumption of the critical loads (AC primary load) is shown in Figure 1. In addition to monthly energy consumption, the daily energy profile (daily AC load) is needed for sizing, simulation, and modeling. Examples of daily loads for weekdays and weekends for the month of August are illustrated in Figure 2.

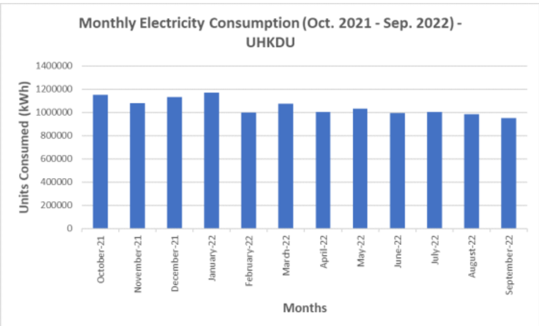


Figure 1. Monthly average energy consumption (Oct. 2021 - Sep. 2022) - UHKDU

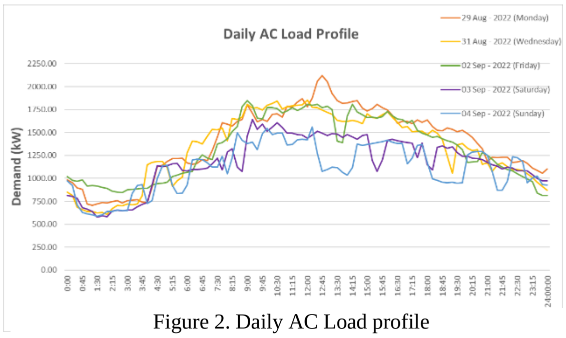


Figure 2. Daily AC Load profile

III. COMPONENT SIZING

A. Solar PV array

It is significant to identify the capacity of the Solar plant that could be installed with maximum utilization of the available rooftop area of the proposed system. Identification of the maximum rooftop Solar PV installation capacity requires computations using equation 1.

$$C_{PV} = \frac{C_{module}}{1000} \times \left(\frac{R \times A_{roof}}{A_{module}} \right) \tag{1}$$

CPV = Potential Solar PV installation capacity (kWp)

Cmodule = The individual module rated capacity (Wp)

R = The roof cover ratio, which is the fraction of roof area that the modules will cover

Aroof = The total roof area available for installation of solar modules (m2)

Amodule = the area of one module (m2)

B. Battery sizing

The calculations of battery capacity were done considering the several cases that could occur due to the worst-case scenarios that could occur in the system. An outage could occur during sun peak hours or off-sun peak hours. Thus, the battery capacity should be sufficient to hold the required load during an outage at any time of the day. The development of a battery storage system by considering a specific period of time of the day may not provide the most economical and effective design. Thus, the following cases were identified and computation of battery capacities was done for each of the scenarios.

Case study 1

An outage of 2 hours during the daytime (during sun peak hours) was considered under case study 1. It was assumed that the outage occurred from 11:30 – 13:30 hours as the maximum demand of the daily load profile of UHKDU was obtained in the daytime. During the daytime, the installed solar plant can be utilized to supply power. During the site survey, it was noticed that the hospital has standby backup diesel generators to compensate for the loss of power during an outage. Thus, subcases of Case study 1 were identified as follows by taking the existing diesel generator and Solar PV generation into consideration.

Sub Case A: Compensation of load is achieved with Solar PV generation & Battery Energy under this subcase. The remainder of solar generation will be exported when the outage is restored.

Sub Case B: The load is compensated with Solar PV generation & Diesel Generator under this subcase. The remainder of solar generation will be exported when the outage is restored.

Sub Case C: The load is compensated with Solar PV generation & partial Battery Energy and partial Diesel Generator. The remainder of solar generation will be exported when the outage is restored.

Case study 2

An outage of 1 hour during the remainder of the day (excluding sun peak hours) is considered under this case. The outage was selected to be from 15:30 – 16:30 hours, which was obtained from the daily load profile where the demand is maximum during the remainder of the day (excluding the period considered in Case study 1).

Sub Case A: The load is compensated with only the Battery Energy storage system. The remainder of solar generation will be exported when the outage is restored.

Sub Case B: The Load is compensated with only Diesel Generator. The remainder of solar generation will be exported when the outage is restored.

Sub Case C: The Load is compensated with partial Battery Energy and partial Diesel Generator. The remainder of solar generation will be exported when the outage is restored.

A worst-case scenario of 90% of peak instantaneous power fluctuation of solar PV is considered due to the formation of clouds for a period of 5 mins within the 2-hour outage duration. Therefore, the battery discharge rate during that time is fixed to compensate for the relevant voltage ramps. Peak shaving is only done on the days when an outage would not occur. The battery is charged during the off-peak time from the grid. Peak shaving duration is considered as 18:30 - 19:00 where the load demand is high, in the peak time region categorized by the electricity provider (CEB) where the tariff rates are high during the day.

C. Inverter Sizing

Computation of the capacity of the inverter was conducted by considering 25-30% higher than the maximum power consumed by the load.

IV. Hybrid Solar PV system Modelling

Using the MATLAB Simulink software, a sample model of the proposed hybrid solar PV system was designed in order to evaluate the functionality of a concept system on a virtual platform. A single-phase solar PV system with a lithium-ion battery energy storage system (BESS) that can function in both isolated and grid-connected modes was created, and its performance was evaluated using the results of simulations. Among the key elements that were modeled throughout the course are the solar PV array, AC-DC bi-directional converter, load and grid, and lithium-ion BESS.

A. Solar PV array

Block for PV arrays in MATLAB Simulink enables users to create custom solar photovoltaic systems using their preferred PV modules from the module database and to set parameters to determine the required capacity of the PV array.

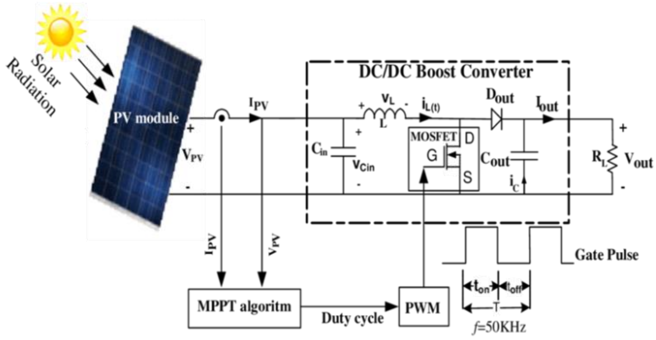


Figure 3. Schematic of a Solar PV array configuration with a boost converter and an MPPT algorithm

Numerous studies on PV cells have been done, including ones on ways to improve a cell's efficiency. The following are some of the fundamental equations for modeling a solar PV module.

Output current (I) of a practical cell,

$$I = I_{PV} - I_o\left[exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] - \left(\frac{V + R_s I}{R_{sh}}\right) \quad (2)$$

I_{PV} is the photovoltaic current and Io is the saturation current of a PV module. V is the cell output voltage and V_t is the thermal voltage of the array. R_s and R_{sh} are series and shunt resistances respectively of a practical PV cell. Diode constant is notated by a, and it is usually a value between 1 and 1.5 according to the studies conducted.

Where diode current (I_d) and Thermal voltage of the array (V_t) can be represented by following equations.

$$I_d = I_o\left[exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] \quad (3)$$

$$V_t = \frac{N_s k T}{q} \quad (4)$$

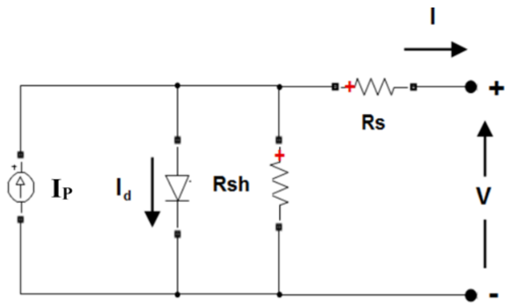


Figure 4. Equivalent circuit of PV cell

Photovoltaic current (I_{PV}) can be calculated as follows,

$$I_{PV} = \left(I_{PV,n} + K_I(T - T_n)\right)\frac{G}{G_n} \quad (5)$$

$I_{PV,n}$ is the photovoltaic current at STC. Short circuit current/temperature coefficient is represented by K_I. T and T_n are actual and nominal temperature respectively whereas G

and G_n stands for irradiation on the device surface and nominal irradiation respectively.

$I_{SC} \approx I_{PV}$ is assumed in most practical cases.

$$I_o = I_{o,n}\left(\frac{T_n}{T}\right)^3 exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n}-\frac{1}{T}\right)\right] \tag{6}$$

Eg is the bandgap energy of the semiconductor (Eg =1.12 eV for the polycrystalline Si at 25 ◦C) [12].

q and k are the electron charge (1.602176x10^{-19} C) and Boltzmann constant (1.3806503x10^{-23} J/K) values.

$$I_{o,n} = \frac{I_{SC,n}}{exp(V_{OC,n}/aV_{t,n}) - 1} \tag{7}$$

$$V_{t,n} = \frac{N_s k T_n}{q} \tag{8}$$

Nominal values of short circuit current, open circuit voltage and thermal voltage are notated by $I_{SC,n}$, $V_{OC,n}$, and $V_{t,n}$.

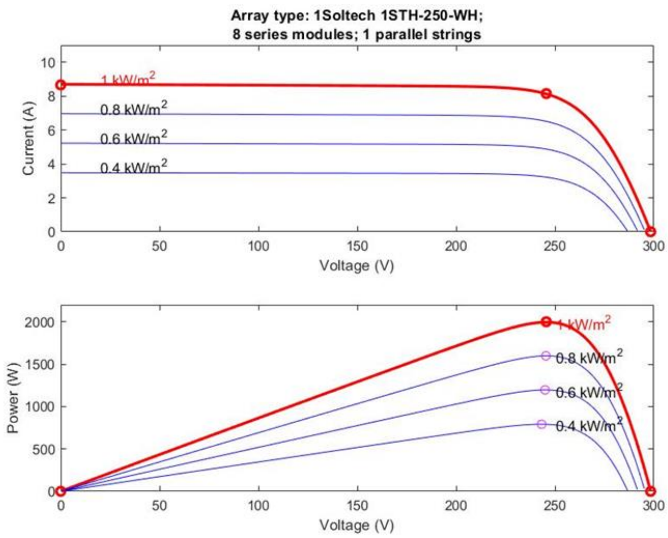


Figure 5. I-V and P-V characteristics at 25°C of the PV array modeled

A boost converter along with an MPPT algorithm was used to step up the generated PV voltage to the DC bus voltage and connect the PV array to the DC bus.

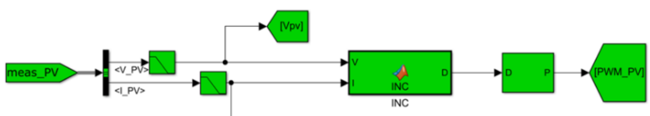


Figure 6. Incremental Conductance MPPT model

Combining all the above subcomponents, a subsystem for Solar PV array was able to model using MATLAB Simulink.

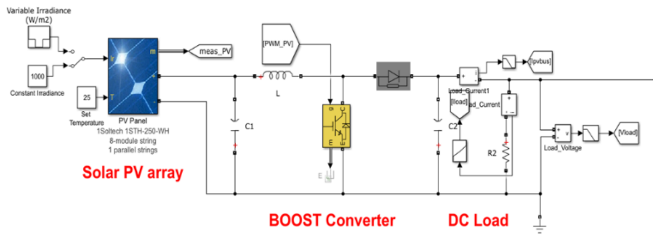


Figure 7. Simulink model of a Solar PV array configuration with a boost converter and an MPPT algorithm

B. AC-DC Bi-Directional Converter

At unity power factor, active power is transferred from the AC bus to the DC bus and vice versa. This is controlled by a bi-directional AC-DC converter. This converter is made up of a converter, an LCL filter circuit, an islanded mode controller circuit, and a grid-connected mode controller circuit.

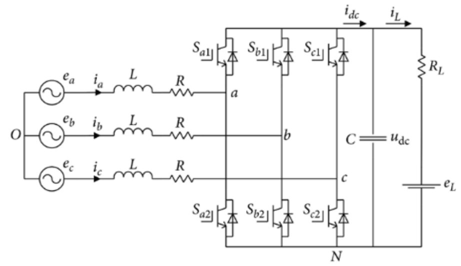


Figure 8. Schematic of a 3 phase AC-DC Bidirectional Converter

Grid connected mode controller circuit and an Islanded mode controller circuit was developed to generate a modulating signal each in respective control operation, so that the modulating signal could be used to generate a PWM signal to trigger the IGBTs in the converter. Harmonics cause the voltage of the system to drop, which lowers the system's quality of power and efficiency. The inverter's output waveforms are more likely to produce these harmonics. LCL filters are therefore used to reduce the impact of harmonics at the inverter.

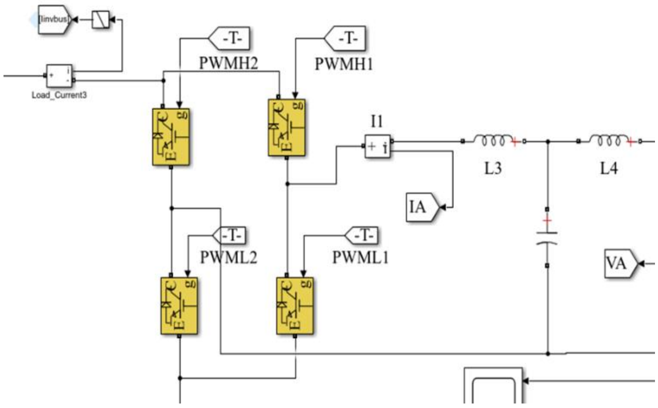


Figure 9. AC-DC bi-directional converter with LCL circuit

C. Li-ion BESS

The parameters of the battery can be set according to the user preference using the Li-ion battery block in MATLAB Simulink.

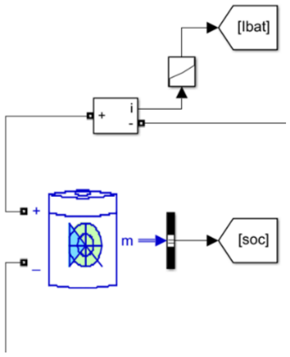


Figure 10. Model of BESS

Figure 11 portrays a circuit which performs bidirectional operation via switching between two MOSFETS Q1 and Q2 and anti-parallel diodes D1 and D2. The diodes behave as freewheeling diodes in the circuits resulting in step up and down of voltage across them. The performance of this circuit can be categorized into two modes namely buck mode and boost mode.

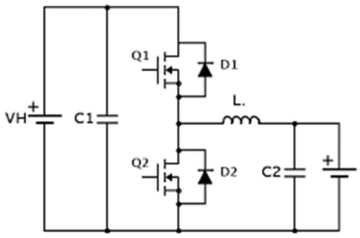


Figure 11. DC-DC bi-directional converter

The Voltage Controller circuit uses the PI controller to generate a duty cycle by comparing the load voltage to the reference voltage. The PWM switching signal for the IGBTs in the DC-DC bi-directional converter is then produced using the duty cycle.

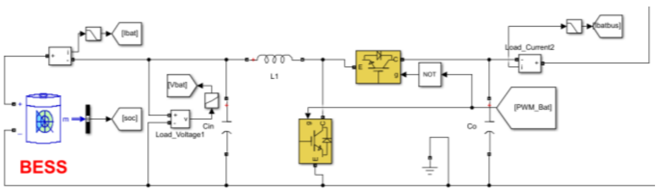


Figure 12. BESS with DC-DC bi-directional converter subsystem

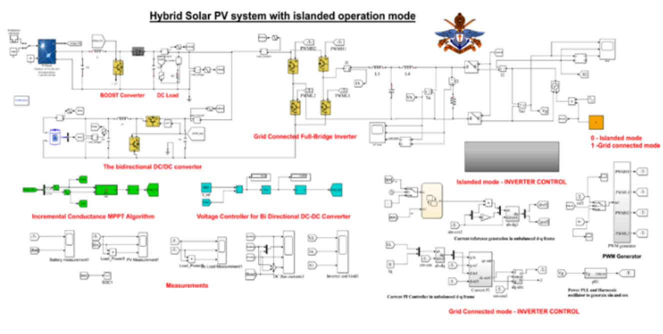


Figure 13. Model of Hybrid Solar PV system

V. Economic Analysis

A. Capital costs

The total investment cost of the proposed design under each case study defined in battery sizing were computed using the existing prices of the components in the market. The total cost of investment comprises of component costs, shipping costs & taxes, installation cost, and replacement cost. Other costs incurred were considered in the LCOE calculations. The capital cost calculation was conducted by considering the following estimations.

- 10% of Solar & Inverter component costs and 15% of the battery component costs are considered as Shipping costs
- 15% of the total component cost is considered as the installation cost of the system
- The replacement cost for each component is considered 25% of their component cost.

B. LCOE

The levelized cost of energy is a metric used to evaluate and contrast different energy production processes. The life-cycle operating costs (LOCE) of an energy source can be calculated as the total cost of installing and maintaining the source for each unit of energy produced over the source's estimated lifetime. The following formulas were used to calculate the LCOE for solar PV system, BESS, and DG for each scenario considered in the economic analysis.

$$LCOE\ of\ solar\ PV\ system = \frac{PC - CBI + \sum_{j=1}^{n}\left(\frac{\left(M(1+r)^j + F\right)\times(1+i)^j}{(1+d)^j}\right)}{\sum_{j=1}^{n}\left(\frac{(1+i)^j}{(1+d)^j}\times Q_o(1-\delta)^j\right)} \tag{9}$$

$$LCOE\ of\ Battery\ or\ DG = \frac{PC - CBI + \sum_{j=1}^{n}\left(\frac{\left(M(1+r)^j + F\right)\times(1+i)^j}{(1+d)^j}\right)}{\sum_{j=1}^{n}\left(\frac{(1+i)^j}{(1+d)^j}\times Q_o\right)} \tag{10}$$

M signifies the annual O&M cost and F is the fuel consumption cost ($/L). Growth rate r is considered to be 2%, discount rate d is considered as 8%, and inflation rate i is considered as 3% which could vary between 3-5% based on the country's economic growth. Project lifetime n is 25 years. Qo is the initial annual electricity output (kWh). The degradation rate is δ which is usually specified in the manufacturer's data sheet for solar panels. *PC* is the project investment cost and *CBI* are the Cost-based incentives.

C. Cost Analysis

Each LCOE was compared against the net monthly cost, net income, savings, payback period for the project investment, and profits made over the course of the project after the break-even point in the cost analysis that was conducted for each scenario. The monthly energy consumption, costs incurred during an outage day, costs incurred during a normal day, and total income obtained exporting solar PV generation were calculated.

The net cost incurred per month is comprised of total unit generation costs of solar PV, battery, and DG per day on a normal day and on a day with an outage for a month, and monthly electricity charges. The net income of each subcase is computed using the total solar generation exported under feed-in-tariff.

VI. OPTIMIZATION USING HOMER PRO SOFTWARE

By using the Homer Pro software for the Optimization and techno economic analysis the foremost factors which contributes for an optimum economical outcome is outlined. The generation of reports with regard to different combinations of the Hybrid solar PV system and obtaining the most economically feasible system based upon net present cost (NPC), the design cost including the initial capital cost, replacement cost, operation and maintenance costs, salvage and interest spent can be obtained.

A. Resource Availability

The site location of UHKDU is given to Homer Pro software, from the software the simulation is located at 6° 49.6′ N latitude and 79° 54.4′ E longitude. The solar availability of afore mentioned location is given in the below figure.

The Annual average horizontal solar radiation of the hospital's location is 5.59kWh/m2/day. Monthly average global horizontal radiation is in the range of 4.930 to 6.670. kWh/m2/day. Also, the annual average temperature value is 26.88 °C, the temperature ranges from 26.41 °C to 27.89 °C to a daily average for a certain month.

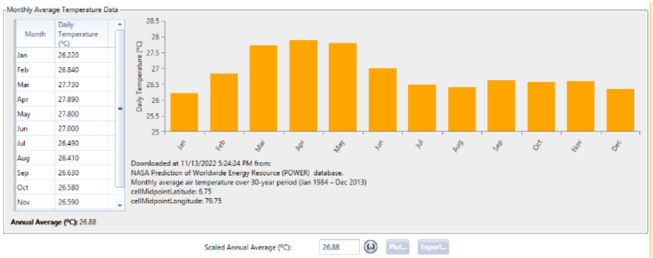


Figure 14. Monthly Average Solar GHI data

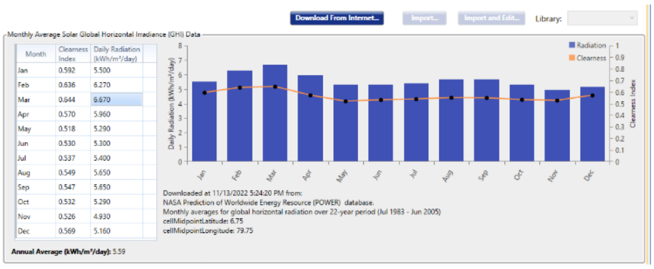


Figure 15. Monthly Average Temperature Data

B. Methodology

The Hybrid solar PV system consists of solar panels, battery energy storage system 2 diesel generators and a convertor as per the energy demand of the institution. The annual average energy demand is 33,500.00kWh/day, and peak demand is 2500 kW. The schematic diagram of the system model designed for the Homer Pro simulation is given below

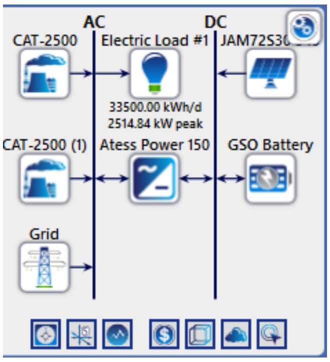


Figure 16. HOMER Pro Hybrid Solar PV system model

The selection of the necessary components for the system the components are selected based on the availability and supplier capability to deliver the components to Sri Lanka.

TABLE I. SELECTED SYSTEM COMPONENTS

Component	Brand and Type
Invertors	Atess Power 150kw Hybrid Invertor
Solar Panels	JA solar JAM72S30 545W Solar Panels
Batteries	GSO battery 200AH Lifepo4 batteries
Generator	CAT 2500kw Diesel Generator (Already available in UHKDU)

1) Load Demand Profiles

The average load demand pattern for the institute was taken from the CEB under a special request from the institute. With the data that was given from CEB the average daily based annual energy demand is 33,500.00kWh/day, which the total annual demand is 12227000kWh/year and which approached to a maximum peak demand value of 2514.84kW.

Figure 17. Average Monthly load profiles.

2) Calculation of the replacement and operation and maintenance costs.

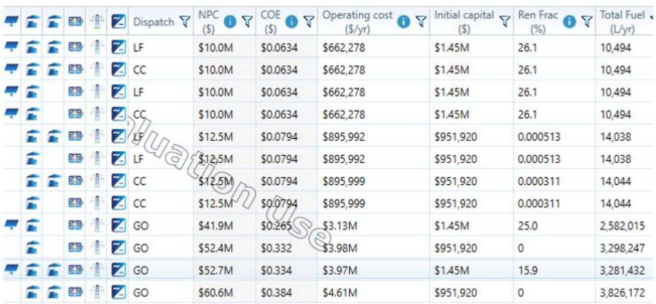
According to the sizing calculations with regard to the rooftop area availability and the capacity that can be implemented, the homer pro software is fed with given below component capacities

For the calculation of Replacement and Operation and maintenance costs, replacement costs are taken as 50% according to the supplier's capability and Operation and maintenance costs are taken as 2% from capital costs with regard to the wages given to the maintenances staff in Sri Lanka.

TABLE II. COST TABLE

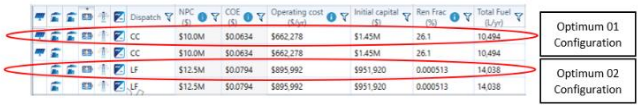
Component	**Cost**	**Tax + Shipping**	**Capital = Cost + shipping Tax**	**Percentage for O&M Per year including Installation cost (from Cost)**	**Replacement 50% (from Capital)**
Solar PV array	$399,087.15	25% = $99,772	$498,860	2% = $7,982	50% = $249,430
3 Phase invertors	$367,200.00	25% = $91,800	$459,000	2% = $7,344	50% = $229,500
Battery Storage	$397,600.00	25% = $99,400	$497,000	2% = $7,952	50% = $248,500

C. *Results and Dicussion*



Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
LF	$10.0M	$0.0634	$662,278	$1.45M	26.1	10,494
CC	$10.0M	$0.0634	$662,278	$1.45M	26.1	10,494
LF	$10.0M	$0.0634	$662,278	$1.45M	26.1	10,494
CC	$10.0M	$0.0634	$662,278	$1.45M	26.1	10,494
LF	$12.5M	$0.0794	$895,992	$951,920	0.000513	14,038
LF	$12.5M	$0.0794	$895,992	$951,920	0.000513	14,038
CC	$12.5M	$0.0794	$895,999	$951,920	0.000311	14,044
CC	$12.5M	$0.0794	$895,999	$951,920	0.000311	14,044
GO	$41.9M	$0.265	$3.13M	$1.45M	25.0	2,582,015
GO	$52.4M	$0.332	$3.98M	$951,920	0	3,298,247
GO	$52.7M	$0.334	$3.97M	$1.45M	15.9	3,281,432
GO	$60.6M	$0.384	$4.61M	$951,920	0	3,826,172

Figure 18. Overall Optimized Results



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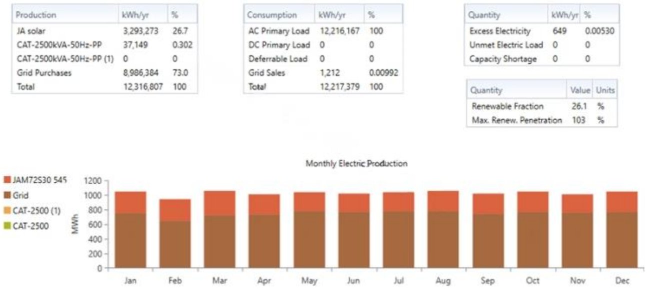
CC	$10.0M	$0.0634	$662,278	$1.45M	26.1	10,494
LF	$12.5M	$0.0794	$895,992	$951,920	0.000513	14,038
LF	$12.5M	$0.0794	$895,992	$951,920	0.000513	14,038

Figure 19. Categorized Optimization Results

Based on the given inputs above, the output results of the HOMER PRO software were obtained for the system optimization consisting of the Renewable source and the other components. Cost details such as Cost of Energy (COE), net present cost (NPC), operating cost and capital costs, details of energy which could be generated by the renewable energy source is given in the above figure 18.

The optimization results show that the most feasible system configuration can be selected based upon the minimum NPC value and Minimum LCOE value. According to the above categorization the minimum NPC value consists of 1900kW Photovoltaics; 200Ah, 48V, 284 lithium Ion batteries; 2676Kw, 18 150kW Hybrid Solar Invertors. The cost factors of the optimum configuration are $10.00M, $0.0634, $662,278, $1.45M for COE, NPC, Operating costs and Initial Capital cost respectively.



Production	kWh/yr	%
JA solar	3,293,273	26.7
CAT-2500kVA-50Hz-PP	37,149	0.302
CAT-2500kVA-50Hz-PP (1)	0	0
Grid Purchases	8,986,384	73.0
Total	12,316,807	100

Consumption	kWh/yr	%
AC Primary Load	12,216,167	100
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	1,212	0.00992
Total	12,217,379	100

Quantity	kWh/yr	%
Excess Electricity	649	0.00530
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	26.1	%
Max. Renew. Penetration	103	%

Figure 20. Production and Consumption of Electricity for the optimum configuration

From the above fig we can identify how the production and consumption of electricity has taken place for the optimum configuration. Based on the values We can generate up to 26.7% of what is consumed as an annual average. From the control strategies and due to the limitation of the solar panels due to limited amount of area, the system is optimized to use its produced energy to meet the load, therefore only a little amount of energy is exported to the grid.

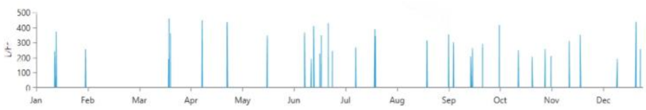


Figure 21. Fuel Consumption during Outages

According to the final report the total fuel consumption for an average year is 10,494L which is 28.8L/day as a daily average. Outages are considered as 36/year, 2h/outage.

1) *Comparison using NPC and COE values*

When considering the optimum 02 configuration as given by the fig66. The initial capital cost for the Optimum 02 configuration is lesser than the optimum 01 configuration because the use of photovoltaics is not initiated in the Optimum 02 configuration. When considering the configurations for a period of 25 years the COE and NPC values of the Optimum 01 Configuration is more Profitable.

2) *Comparison using Gas emissions*

If we compare the gas emissions of the proposed HRES with the conventional coal-based power plants, the gas emission of the conventional power plant would be 0.814 kg/kWh for CO2, 4.631 g/kWh for CO, 5.823 g/kWh for SO2, and 2.230 g/kWh for NO. The total energy consumed by the hospital load per year is 12216185kwH/year as an average. Which this would emit 9,943,974.59kg of CO2, 46,050kg of CO, 268,152kg of SO2 and 597,979kg of NO if only based on coal-based power plants.

From the above configurations the systems with renewable energy and without renewable energy are categorized into 2 main configurations as config. 01 and config. 02.

Quantity	Value	Units
Carbon Dioxide	5,707,142	kg/yr
Carbon Monoxide	11.4	kg/yr
Unburned Hydrocarbons	0.630	kg/yr
Particulate Matter	0.630	kg/yr
Sulfur Dioxide	24,692	kg/yr
Nitrogen Oxides	12,199	kg/yr

Figure 22. Gas emissions with renewable energy - optimum 1

Quantity	Value	Units
Carbon Dioxide	7,724,642	kg/yr
Carbon Monoxide	15.3	kg/yr
Unburned Hydrocarbons	0.842	kg/yr
Particulate Matter	0.842	kg/yr
Sulfur Dioxide	33,421	kg/yr
Nitrogen Oxides	16,510	kg/yr

Figure 23. Gas emissions without renewable energy - optimum

Upon comparison of the 2 configurations the gas emissions of the System with the renewable energy is lesser than the system without renewable energy. Therefore, it is apparent that more priority should be given to renewable energy generation, and with regard to this config. 01 is selected.

3) Net Present Cost Breakup Analysis

Component	Capital($)	Replacement($)	O&M($)	Fuel($)	Salvage($)	Total($)
Invertor	$454,920.00	$0.00	$94,095.77	$0.00	$0.00	$549,015.77
Generator	$0.00	$0.00	$0.00	$162,799.78	$0.00	$162,799.78
Battery	$497,000.00	$105,432.05	$102,799.61	$0.00	($19,843.38)	$685,388.28
Grid	$0.00	$0.00	$8,013,132.48	$0.00	$0.00	$8,013,132.48
Photovoltaics	$498,860.00	$0.00	$103,187.44	$0.00	$0.00	$602,047.44
System	$1,450,780.00	$105,432.05	$8,313,215.30	$162,799.78	($19,843.38)	$10,012,383.76

Figure 24. Optimum 01 Configuration

Component	Capital($)	Replacement($)	O&M($)	Fuel($)	Salvage($)	Total($)
Invertor	$454,920.00	$0.00	$94,095.77	$0.00	$0.00	$549,015.77
Generator	$0.00	$0.00	$0.00	$217,771.89	$0.00	$217,771.89
Battery	$497,000.00	$105,432.05	$102,799.61	$0.00	($19,843.38)	$685,388.28
Grid	$0.00	$0.00	$11,082,694.03	$0.00	$0.00	$11,082,694.03
System	$951,920.00	$105,432.05	$11,279,589.42	$217,771.89	($19,843.38)	$12,534,869.98

Figure 25. Optimum 02 Configuration

4) Sensitivity analysis

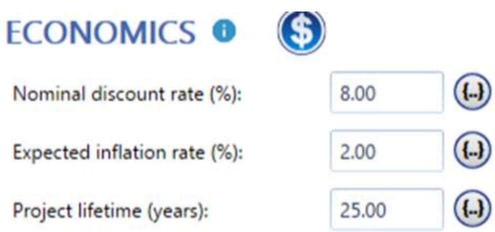


Figure 26. Inputs of the Sensitivity Analysis

Based on the inputs of the sensitivity analysis the nominal fixed discount rate for the system is taken as 8.00% annually, by this the O&M cost the price of the components degrades by 8% year. The expected inflation rate is taken as 2% which due to inflation the net cost of the components does gets increased by 2% annually. The chart given below is the cost analysis for the system based upon the Nominal discounted rate.

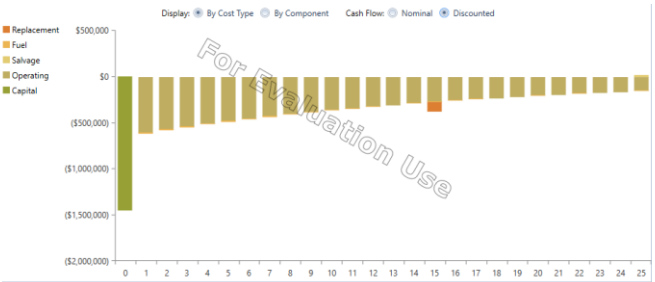


Figure 27. Cost analysis for the system

RESULTS AND DISCUSSION

The preliminary site assessment of the hospital concluded on the location of the hospital obtaining the required solar GHI, temperature, and weather throughout the year to support this proposed design. As a result of a comprehensive analysis of the load requirement of the hospital, the average daily demand of the hospital was identified as 33 MWh.

The total Solar generation for an average day is 8269 kWh. Preceding a thorough site survey, the possibility of a 1.9 MW Solar Plant was identified.

The Peak demand obtained from the load profile is 2121.56 kW. With an inverter design margin of 25% required inverter capacity was found to be 2651.95kW. By considering factors such as cost, efficiency, and practicality the selected rating for the inverter in the proposed design was 150 kW.

The computation of the capacity of battery storage was done by considering two case studies by assuming the worst possible events that could occur in the system. If an outage occurs during sun peak hours, the power generated from the Solar plant can be utilized along with the energy from battery storage system. Yet in the Off-sun peak hours (15;30 – 08:30 hrs), the battery will solely have to supply the load demand. Additionally, instead of using the battery independently, the power generation could be shared among the existing diesel generator and battery. The Table 4.4- 4.7 depicts the capacities of 400Ah Li-ion battery capacities for each subcase of the proposed design.

TABLE III. SUMMARY OF BATTERY SIZING-CASE 1. A

CASE 1 – Sub Case A		
	Peak shave & Outage	***Only outage***
Load to be met by a battery	451.60 kWh	451.60 kWh
Load to be met during Peak Shaving (18:30-19:00)	764.63 kWh	0.00 kWh
Total Load to be met during one discharging cycle	1216.23 kWh	451.60 kWh
The total energy required by ESS during a daytime outage	764.63 kWh	544.56 kWh
Battery Capacity required	24751.05 Ah	17627.29 Ah
No. of batteries needed	62	45

TABLE IV. SUMMARY OF BATTERY SIZING-CASE 1. C

CASE 1 – Sub Case C	
	Only Outage
Load to be met by a battery	225.80 kWh
Load to be met during Peak Shaving (18:30-19:00)	0.00 kWh
Total Load to be met during one discharging cycle	225.80 kWh
The total energy required during a daytime outage	318.76 kWh
Battery Capacity required	10318.2 Ah
No. of batteries needed	26

TABLE V. SUMMARY OF BATTERY SIZING-CASE 2. A

CASE 2 – Sub Case A	
	Outage Only ***(Peak shave considered)***
Load to be met by battery (1hr)	1727.36 kWh
Load to be met during Peak Shaving (18:30-19:00)	764.63 kWh
Total Load to be met during one discharging cycle	2491.99 kWh
The total energy required during an outage	1753.10 kWh
Battery Capacity required	56747.380 Ah
No. of batteries needed	142

TABLE VI. SUMMARY OF BATTERY SIZING-CASE 2. C

CASE 2 – Sub Case C	
	Outage Only ***(Peak shave considered)***
Load to be met by battery (0.5hr)	886.37 kWh
Load to be met during Peak Shaving (18:30-19:00)	764.63 kWh
Total Load to be met during one discharging cycle	1651.01 kWh
Nominal Voltage of a battery	48 V
Rated capacity of a battery	400 Ah
The total energy required during an outage	894.16 kWh
Battery Capacity required	28943.73 Ah
No. of batteries needed	73

In this study, MATLAB Simulink software was utilized to model the scaled hybrid Solar PV system to analyze the seamless transfer between two modes of operation and constant output power. Components of the system architecture were modeled and then combined to obtain seamless transfer between the islanded mode and gird-tied mode. Thus, the Simulink model was simulated under two considerations; Islanded mode and Grid-tied mode.

1) *Islanded Mode*

The islanded mode denotes a power outage of the system. Thus, it is important to supply constant power to load in this condition. The figure 28 is the output waveform of the system which depicts a constant output power.

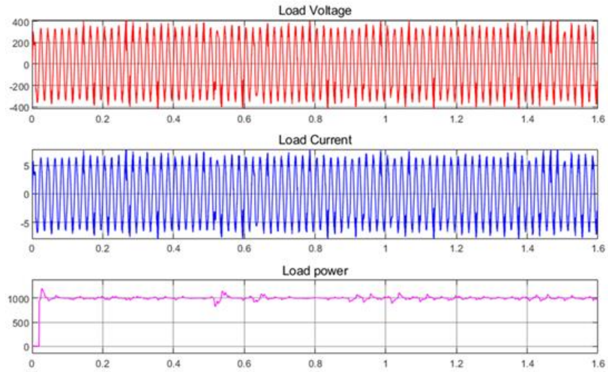


Figure 28. Islanded Mode-Load Voltage, Current and Power

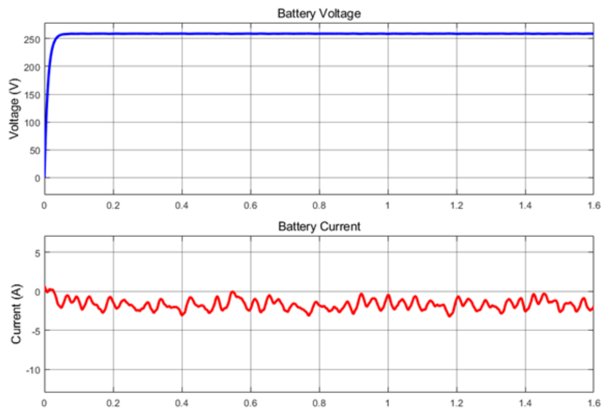


Figure 29. Islanded mode: Battery voltage and current

2) *Grid connected Mode*

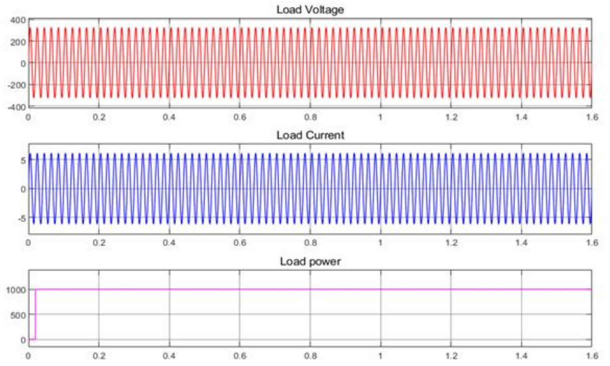


Figure 30. Grid connected mode: Load Voltage, Current and Power

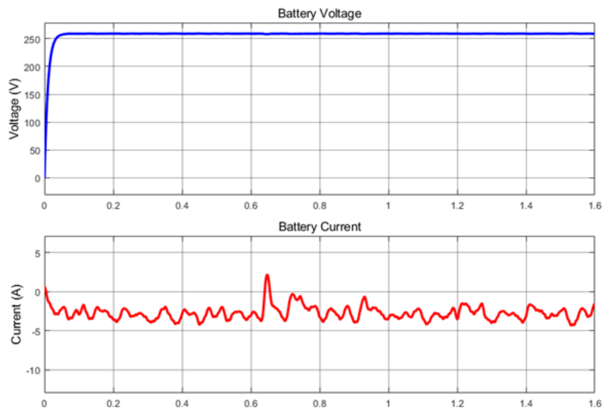


Figure 31. Grid connected mode- Battery output waveform.

The capital post of all proposed components except for the already existing Diesel generator was computed concerning the investment, shipping & taxes, and maintenance cost. Computations of the capital cost was conducted for each subcase considering the performance of peak shaving and providing during an outage. The difference in capital costs of each case depends on the capacity of the battery storage system as the rest of the components remain constant for each case. An investment cost of $1,765,711 is incurred under case two: subcase A where the demand during an outage is compensated using 142 batteries, making it the highest incurred cost out of all the cases. This storage capacity was computed to supply power for an outage of one hour for the maximum demand in off-sun peak hours and it could be used to shave the peak demand on normal days and obtain monetary benefits.

TABLE VII. SUMMARY OF CAPITAL COST OF CASE STUDY 1

Capital Costs for Case 1	**Sub Cases A & B**		**Sub Case C**
	Outage & peak shaving	**Only outage**	**Only outage Case C**
Total Investment Cost	$1,418,511.00	$1,344,731	$1,258,631

TABLE VIII. SUMMARY OF CAPITAL COST OF CASE STUDY 2

Capital Costs for Case 2	**Sub Cases A & B**	**Sub Case C**
	Only Outage (peak shave included)	**Only outage Case C**
Total Investment Cost	$1,765,711	$1,456,031

Certain parameters such as Net present value and Levelized Cost of Energy were calculated. In order to perform precise calculations factors such as fuel consumption rates of diesel generators under each subcase, feed-in tariff, Inflation, and discount factors were analyzed. Table 4.10 and table 4.11 depicts the summarized LCOE values of each subcase which will be used to analyze the gains and costs of the proposed design.

TABLE IX. CASE 1 LCOE SUMMARY

CASE 1 LCOE Summary		
1. Sub Case A: LCOE for Battery (with peak shave)	0.058 $/kWh	21.02 Rs./kWh
2. Sub Case B: LCOE for DG (with peak shave)	0.680 $/kWh	244.75 Rs./kWh
3. Sub Case A: LCOE for Battery (only outage)	0.483 $/kWh	173.83 Rs./kWh
4. Sub Case B: LCOE for DG (only outage)	0.770 $/kWh	277.34 Rs./kWh
5. Sub Case C: LCOE for Battery + DG (only outage)	0.773 $/kWh	278.42 Rs./kWh

TABLE X. CASE 2 LCOE SUMMARY

CASE 2 LCOE Summary		
1. Sub Case A: LCOE for Battery	0.057 $/kWh	20.56 Rs./kWh
2. Sub Case B: LCOE for DG	0.363 $/kWh	130.71 Rs./kWh
3. Sub Case C: LCOE for Battery + DG	0.108 $/kWh	38.83 Rs./kWh

The common notion of adopting Hybrid Solar PV systems is the inability to obtain monetary benefits due to high expenses on the installation of such systems. In special circumstances such as the UHKDU where a standby diesel generator is already established to compensate for the redundant power, installation of an alternative power system incorporating renewable energy such as this study may be profitless. Thus, this study investigates the veracity of such conceptions. The subcases under Case 1 depict the Net savings and profits gained over a lifespan of 25 years that could be achieved from various capacities of battery storage systems during the sun peak hours. Subcase A with the capability to peak shave and supply during power requires 62 batteries of rating 400Ah. It provides a net saving of $24259.29 leading to the highest saving compared to Subcase C and Subcase A which only provides for an outage. Thus, usage of 62 batteries is beneficial as not only could it compensate during an outage but also peak shave during peak demand hours which will support demand side management of the overall power system. Case 2 discusses the scenarios where the load is taken care of solely by battery and generator due to the absence of solar power generation. Subcase A provides the highest saving compared to all the cases while utilizing 142 batteries. It was established that subcase A under case 1 which requires 62 batteries cannot compensate for the demand during off-sun peak hours as its capacity is not sufficient. The demand could not be held even for an hour using 62 batteries. Thus, compared to all the cases Subcase A under case 2 seems to be the most effective and economical option for the proposed system.

The current existing backup power system at UHKDU has an installed capacity of 7. 2MW.Subcase B under both scenarios used the diesel generator to compensate for the demand. In subcase b of case 1, the generator supplies the outage demand along with Solar power and thus the generator could be used to participate in peak shaving as it does not incur significant loss compared to solely using the generator to compensate for the demand during an outage. Even though the installation cost of the generator is not considered for the calculations in table 4.13, generators incur a daily running cost with the quantity of fuel used. Thus, compared to the usage of 142 batteries to compensate for the demand during an outage and peak shave on days where an outage does not occur, the savings obtained from the diesel generator are less. In fact, in each case, 1 & 2 the incurred saving from using diesel generator is very low. Thus, it could be established that incorporating batteries provides a massive economic benefit and by implication, fewer adverse effects on the environment. As shown under subcase A of case study 2, usage of 142 batteries provides the highest savings compared to all the cases.

TABLE XI. COST ANALYSIS

	Case 1					Case 2		
	1.Sub Case A (peak shave + outage)	**2. Sub Case B (peak shave + outage)**	**3. Sub Case A (Outage Only)**	**4. Sub Case B (outage only)**	**5. Sub Case C (outage only)**	**1. Sub Case A**	**2. Sub Case B**	**3. Sub Case C**
Nett Cost incurred per month	$81,671.00	$96,638.00	$82,296.00	$82,702.00	$82,750.00	$81,753.00	$83,071.00	$82,774.00
Exported solar pv generation (kWh)	237788.00	237788.00	237788.00	237788.00	236971.00	248076.00	248076.00	248076.00
Feed-in-tariff ($/kWh)	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096
Nett Income	$22,788.00	$22,788.00	$22,788.00	$22,788.00	$22,709.70	$23,774.00	$23,774.00	$23,774.00
Regular Electricity consumption charges per month	83142.31	83142.31	83142.31	83142.31	83142.31	83142.31	83142.31	83142.31
Nett Savings	$24,259.37	$9,292.00	$23,634.00	$23,228.00	$23,101.00	$25,163.00	$23,845.00	$24,141.00
Payback period for the Hybrid Solar PV system (years)	4.87	-	4.74	-	4.54	5.85	-	5.03
Profits gained over the project lifespan (25 years)	$5,859,276.00	-	$5,745,545.00	-	$5,671,830.00	$5,783,268.00	-	$5,786,385.50

Comparison between subcase A of both cases 1 & 2 also shows that even though 142 has a higher investment cost, it provides the capability to sustain an outage of more than 2 hours during the sun peak hours and also higher saving of the peak demand.

CONCLUSION

The fundamental objective of the study was to design a Hybrid Solar PV system with the capability of islanded operation to compensate for the power deficit during an outage and thereby use it as an alternative to diesel generators. The rapid spread of Covid -19 pandemic resulted in the rising demand for the health sector around the world. Concurrently, a sudden increment of power outages and fuel price hikes resulted in the island with the economic crisis and fossil fuel shortage. The health sector was compelled to rely on standby back power diesel generators to provide uninterrupted power supply to the vital machinery. With the inflation and sudden surge in the usage of DGs, the expense of fuel was increased resulting in an increase in the carbon footprint.

The proposed Hybrid Solar PV system consists of a 1.9MW rooftop solar PV plant along with a battery capacity of 2.7 MWh to cater to the demand during a power outage during sun peak hours or off-peak hours. It was estimated an average of 3.02 GWh of solar PV generation can be produced from this solar PV plant per annum. The hybrid power system includes two main energy sources namely solar PV and Lithium-ion BESS, and a DC-AC Bi-directional converter.

A thorough economic analysis was conducted to identify the suitable capacities of the components. It was identified that the usage of 142 units of 400Ah batteries provided the highest profit over the estimated lifetime of the system, resulting in a total payback period of 5.85 years with an investment cost of $1,765,711 for the system. Thus, the proposed design could meet the daily electrical demand during a power outage and provide the capability of peak shaving during ordinary days. The project could generate profits up to an estimation of $5.5 Mn based on the control strategies used in the system over the period of the project lifespan. Installation of such a system will increase renewable energy penetration and reduce fuel costs and the emission of greenhouse gases (GHG) to the environment.

The proposed design was modeled and simulated using MATLAB Simulink to observe its performance under grid-tied mode and islanded mode. HOMER Pro software was used to obtain a techno-economic analysis of the system and conclude the optimum configuration of the Hybrid Solar PV system and respective control strategies.

This research promotes the concept of microgrids integrated with renewable energy sources, which are directly assisting the efforts undertaken by the Sri Lankan government towards the development of the renewable energy sector. A similar approach to the proposed hybrid system design can be further developed to be implemented in factories, banks, military facilities, high-security facilities, etc. The concept of microgrids using renewable energy sources can also be normalized in society through this study.

REFERENCES

[1] Y. Zhou, J. A. Ferreira and P. Bauer, "Grid-connected and islanded operation of a hybrid power system," 2007.

[2] . IEEE Electron Devices Society, . Annual IEEE Computer Conference, F. IEEE Photovoltaic Specialists Conference 39 2013.06.16-21 Tampa, F. PVSC 39 2013.06.16-21 Tampa and F. IEEE PV Specialists Conference 39 2013.06.16-21 Tampa, 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC) 16-21 June 2013, Tampa, Florida.

[3] On the policy of photovoltaic and diesel generation mix for an off-grid site: East Malaysian perspectives, "On the policy of photovoltaic and diesel generation mix for an off-grid site: East Malaysian perspectives," *Solar Energy,* vol. 74, no. 6, pp. 453-467, 2003.

[4] Nafeh, Abd El-Shafy A., "Design and Economic Analysis of a Stand-Alone PV System to Electrify a Remote Area Household in Egypt," *The Open Renewable Energy Journal,* vol. 2, no. 1, pp. 33-37, 2009.

[5] C. Ghenai, T. Salameh and A. Merabet, "Design, Optimization and Control of Standalone Solar PV/Fuel Cell Hybrid Power System".

[6] Alramlawi, Mansour; Gabash, Aouss; Mohagheghi, Erfan; Li, Pu, "Optimal operation of hybrid PV-battery system considering grid scheduled blackouts and battery lifetime," *Solar Energy,* vol. 168, pp. 125-137, 2018.

[7] D. Kucevic, L. Semmelmann, N. Collath, A. Jossen and H. Hesse, "Peak Shaving with Battery Energy Storage Systems in Distribution Grids: A Novel Approach to Reduce Local and Global Peak Loads," *Electricity,* vol. 2, no. 4, pp. 573-589, 2021.

[8] S. G. K. C. Y. a. B. T. K. Thirugnanam, "Battery integrated solar photovoltaic energy management system for micro-grid," *Smart Grid Technologies - Asia (ISGT ASIA), 2015 IEEE Innovative,,* pp. 1-7. , 2015.

[9] B. S. A. L. V. A. C. a. K.-A.-H. N. Adhikari, "Analysis and design of isolated solar-PV energy generating system," *Industry Applications Society Annual Meeting (IAS), 2011 IEEE, Orlando, FL,* pp. 1-6., 2011.

[10] M. C. a. V. G. A. G. Wang, "Power Smoothing of Large Solar PV Plant Using Hybrid Energy Storage," *IEEE Transactions on Sustainable Energy,* vol. 5, no. 3, pp. 834-842, 2014.

[11] . Institute of Electrical and Electronics Engineers, . IEEE Communications Society and . Vehicular Technology Society. Portugal Chapter, 2014 21st International Conference on Telecommunications (ICT) took place 4-7 May 2014 in Lisbon, Portugal..

[12] G. Walker, "Evaluating MPPT converter topologies using a matlab PV mode," *J. Elect. Electron,* vol. 21, no. 1, p. 45–55, 2001.