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Impact of Energy Management on a Solar Photovoltaic Microgrid

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Abstract*: A bigger percentage of known primary sources of energy is fossil fuel. The energy consumption is rapidly increasing all over the world but their real sources generally remain limited. As the world fossil fuel production rate stands, many major producer countries will deplete their oil fields within a decade calling for some other alternative sources of energy production. Investing in renewable energy resources as an alternative to fossil fuel burning has been on the rise with solar photovoltaic taking the lead in supplying a clean environmentally friendly renewable energy resource using solar photovoltaic technology. Fossil fuel burning also causes global warming and consequent destruction of ozone layer. This paper presents the impact of energy management on a solar photovoltaic microgrid. Literature related to solar photo-microgrid reviewed from various researchers, mathematical modeling, energy management, and weather forecast of the microgrid studied. Furthermore, the economic and environmental impact of installing the solar PV system to supplement the utility grid electricity studied. The microgrid modeling done in MATLAB/Simulink software, hardware components assembled and Arduino Uno used to implement the energy management system in real-time. The weather forecast that led to estimation of future solar power production done using both PVsyst and Application Programming Interface (API) software for medium term and short term planning respectively. The economic analysis of the proposed solar PV system show that the initial cost of investing in the solar PV system is US$ 384, the payback period estimated at 11 years while the overall saving gained by switching from the utility grid electricity to solar PV system for 25 years estimated at US$ 486. The energy management achieved through switching between the PV based microgrid and the utility grid electricity is able to reduce 1,333.78 kg of CO2 emissions during the 25 years of the project life.

Keywords:* Economic Feasibility, Energy Management, Grid-Connected PV system, Weather Forecasting.

I. INTRODUCTION

Electricity is an essential service for people in most community activities like in households, office and industry. World nations are targeting emission reductions with a view to reach net zero by the year 2030 through phasing out fossil fuel burning and encouraging investment in renewables [1]. Solar power ranked top among renewable energy sources currently on the rise. Kenya's solar potential is favorable for Photovoltaic (PV) power generation estimated at an average irradiance of 5.74 kWh/m^2 per day by PVsyst photovoltaic software. Solar energy depends on changing weather pattern, is only available during the day and a clear weather. On a sunny day, solar panel receives a higher insolation than on a cloudy day.

For continuity of power supply, there is need to store surplus energy when the weather conditions are favorable and this stored energy used during poor weather or during the night. Batteries are preferred for electricity storage services. Shadow, dust, snow, and rain affects the solar cell output power [2]. Mathematical modeling of the microgrid done using MATLAB/Simulink software and simulated for better understanding of the solar PV physical system. The energy balance between the utility grid electricity and the renewable energy resource is necessary for efficient utilization of solar power.

The Arduino microcontroller and sensors are alternative ways to regulate the energy balance in the microgrid. The electricity consumer uses accurate weather forecast software to predict the solar photovoltaic power production useful for short term and medium term planning. An Application Programming Interface (API) provides a short-term weather forecast for 7 days ahead, data that is necessary for energy planning. API predicts solar radiation parameters based on Google search. Live and forecast solar data is downloadable using the software [3]. The technology is new to solar PV studies. Medium term weather forecast covering a period of up to one year is also possible using PVsyst photovoltaic software.

This study assessed the impact of energy management on a solar photovoltaic microgrid implemented in the laboratory at Murang'a University of Technology. The solar resource potential of the study area assessed and the future PV power production performance of a 90 W microgrid system installed predicted based on the solar PV resource software programs available in the internet. The feasibility of the solar PV system relative to the national electric grid and environmental impact of installing the solar PV system is extensively studied.

Section II of this paper presents related research on solar photo-microgrids, section III presents the materials and methodology used, section IV discusses the results, and section V is conclusion and future work of the study.

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II. LITERATURE REVIEW

The production of energy by burning of fossil fuel results in greenhouse gas (GHG) emission into the atmosphere. For the last few decades, the reduction of GHG emission has been an important target for many countries. This has led to generation of electrical energy by cleaner ways. Solar power is an alternative renewable energy source to fossil fuel producing cleaner and cost effective electricity through solar PV technology. According to the International Renewable Energy Agency, the total capacity of installed solar PV globally estimated at 700 GW by the end of the year 2020 [4]. In recent years, phenomenal growth in solar energy has been due to technological advancement that reduces the cost of solar products and government incentive policies in support of renewable energy developments and utilization. Lack of proper knowledge amongst the consumers accompanied by low quality solar products in the market affects its growth.

A number of studies conducted on solar PV systems are on microgrid modeling, energy management and feasibility studies topping the studies over span of time. Many researchers apply detailed mathematical formulations to represent the actual working of PV systems, which are later simulated using appropriate simulation software to determine the actual performance of the PV system leading to better understanding of the system under study. Reference [5] applied MATLAB/Simulink software to model a solar PV system connected to electricity grid and outlined the characteristics of the PV module and associated component controls. The study did not address the energy management between the utility grid and the renewable energy source. Reference [6] modeled a smart grid aiming to maintain energy sustainability in the smart grid consisting of solar PV, energy storage system, electric vehicle, utility grid, and loads. Real-time implementation of the system not realized in the study.

As an autonomous energy resource unit, a solar PV system should be provided with an embedded energy management control unit to manage the energy generated and improve sustainability at low cost of investment. Microcontrollers employed for the purpose of energy management system in real-time. The microcontroller is good for getting real-world analogue signals to a computer and sending digital signals from the computer to the real world since its processing chip has direct access to both the input and output pins. A load management system using Arduino microcontroller designed and implemented to improve the continuity of solar power supply for a household in Indonesia [7]. Battery capacity used as reference for the relay to switch to State Electricity Company (backup) when the battery capacity dropped below 10%. High load, medium load and low load operated one at a time not all at the same time making some loads idle. Reference [8] applied Arduino microcontroller and sensors to switch between a high priority load and a low priority load when load shading occurs by tripping the low priority circuit but not the high priority circuit. Related data like current, voltage and power displayed on an LCD display. Reference [9] utilized Arduino microcontroller for decision-making and operation for economic power dispatch in both on-grid and off-grid power generation systems.

The emerging trend of estimating future solar PV power generation is by applying suitable weather forecasting software having the capability to predict the amount of solar photovoltaic radiation and other solar related parameters for the study area. Reference [10] applied PVsyst simulation software to simulate PV power production from two installation sites in the regions of Rabigh and Yanbu Saudi Arabia. The expected total solar power generation for 25 years from the regions determined but the exact quantity of CO_2 reduced from the study not stated despite the emission reduction guidelines specified in the study. Reference [11] modeled a solar PV plant using PVsyst in the Pakistan's Islamia University of Bahawalpur to replace the conventional energy from the utility grid with the environment-friendly, grid-connected, solar PV energy in the institution. There was a need to address the effect of environmental conditions on PV modules too. Reference [12] proposed a one day ahead weather prediction model capable of forecasting solar radiation parameters based on the previous day meteorological data obtained from the nearby meteorological site. This prediction enabled estimation of energy production leading to economic power dispatch but there was a need to use forecast weather data that could lead to estimation of energy production for a number of days ahead. The Solcast's global performance data validated on an hourly Global horizontal irradiance (GHI) [13]. The study strengthened the application of API as a tool applicable to future photovoltaic studies. A feasibility study is always necessary, as the first step towards setting up a successful renewable energy project to find out if the project is financially and technologically viable. The feasibility study helps identify the roadblocks of the solar projects at the start of the planning phase and is advantageous because it helps limit the project risks and address issues early. With no thorough feasibility study, solar projects are more likely to stall or go over budget but when identified before project initiation, many critical design constraints overcome. There are various alternatives taken before investing in a solar PV project to maximize profitability of such projects and that the benefits out way the risks [14]. The economic feasibility of installing a grid connected solar PV system for a home in Bhutan showed that it was not financially viable considering the current price of electricity in Bhutan [15]. However, the investment proved more cost effective than grid-line extension. The study only relied on secondary solar resource data, no ground measurement and on-site survey conducted. Reference [16] compared the profitability index of installing a solar PV system for a family home in three different European countries. The results showed that PV system is very profitable in Germany despite the low solar irradiation and low PV power production than Spain and Croatia having higher solar irradiation. This is because of higher electricity prices in Germany leading to higher savings.

Solar technology does not require combustion of fossil fuel, which releases harmful pollutants into the atmosphere thus lowering the GHG emission. Human activities declared the main source of GHG emission (mainly CO2) into the atmosphere according to the United States Environmental Protection Agency [17].

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Despite the many studies conducted as in the literature, there is still wider research gap in PV power generation in order to meet and satisfy exponential rise in renewable energy targets like reliability, feasibility and to combat climate change.

III. MATERIALS AND METHODS

A. Microgrid Modeling

1) PV Modeling

The power output of a PV panel depends on the solar irradiance, area of the PV panel, the panel efficiency, and the ambient temperature. The panel output power expressed as in [18].

$$P_{PV} = GA\eta\{1-\gamma(T-25)\} \quad (1)$$

where P_{PV} denotes the panel output power, G, A, and η denote the solar irradiance, PV module area, and the conversion efficiency of the PV module respectively, γ and T denote coefficient of temperature and ambient temperature in $^{\circ}C$ respectively. User-defined Simulink model for the solar PV module used for the modeling.

2) Battery Modeling

The battery works as a load when charging and as an energy source when discharging. The net capacity of a battery expressed as in [19].

$$Cb_{net} = E / V \quad (2)$$

where Cb_{net} denotes the net capacity of the battery in Ah per day, E and V denote the total energy in Wh and the system DC operating voltage respectively. The battery is a charge-dependent voltage source and its state of charge (SOC), which is the remaining power of a battery expressed as in [20].

$$SOC = \left(Cb_{remaining} / Cb_{present}\right) \times 100\% \quad (3)$$

where $Cb_{remaining}$ and $Cb_{present}$ denote the remaining capacity and the current maximum capacity in Ah of the battery respectively. User-defined Lead-Acid generic battery model available in the Simscape library used in the modeling.

3) Inverter Modeling

A power inverter converts the DC output voltage from both the PV module and the energy storage system into AC voltage in order to supply the rated A.C loads. A unidirectional Insulated Gate Bipolar Transistor bridge inverter connected to operate between the micro sources and the load with its output voltage, polarity, and frequency synchronized to the utility grid electricity. Inverter models available in the Simulink library used for the modeling.

4) Grid Modeling

The connected loads had a nominal voltage rating of 240 V supplied from the state electricity grid operating at 11 kV through 11kV/400V step down transformer. User-defined models are available in the Simscape power system library.

5) Complete Model of the Grid-connected Solar PV System

The complete Simulink model of interconnected subsystems for the solar PV system shown in Fig. 1. The DC voltage from the solar PV module is available in DC bus which is usually a lengthy cable acting as a link between the solar PV module and the power inverter (DC-link). EMS is the energy management subsystem modeled to manage the microgrid energy flow, the scopes included for ease of monitoring the state of related parameters including the energy flow analysis.

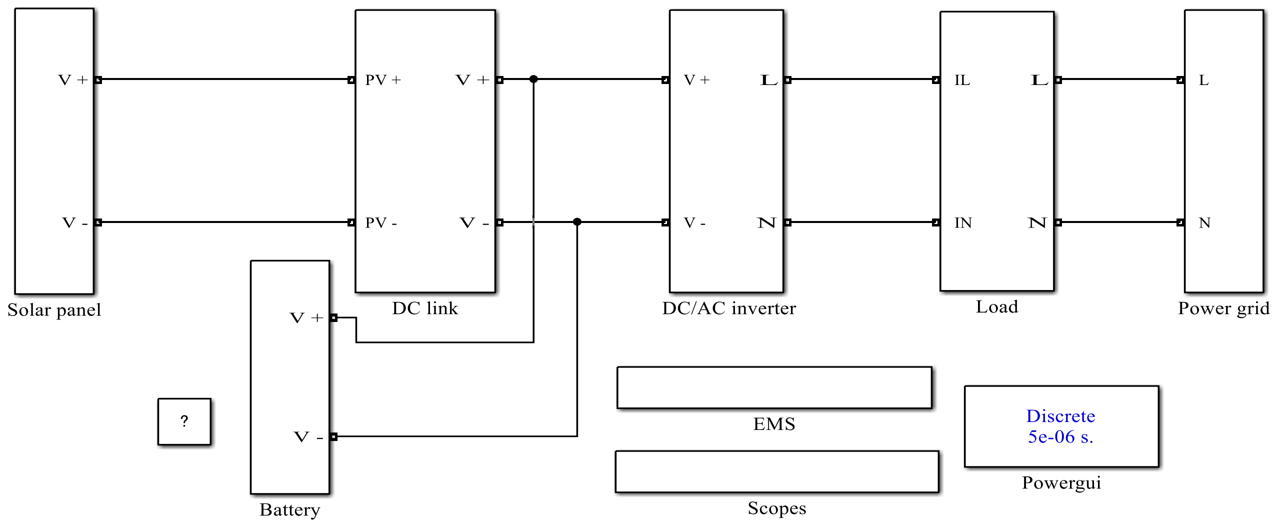

Fig. 1. Simulink model of the solar PV system

B. Solar PV System Sizing

The PV system sizing considered estimating the consumer load size, determination of the required output power of the PV module, sufficient storage capacity of the battery and means of connection to the utility grid via inverter.

1) Load Estimation

Three energy saving bulbs with different power ratings were used as consumer loads. The ratings and usage of the loads shown in Table I.

The bulbs supplied at 240 V, 50 Hz single-phase source.

2) Solar PV Module Sizing

In sizing the PV module, the total daily load in Watt-hours is determined and the average sun hours of the study area estimated using appropriate software or Google-search. The maximum output power of the PV module determined by using (4).

$$P_T = E_D / h \quad (4)$$

where P_T denotes the maximum output power of the PV module, E_D denotes the total load demand in kWh per day and h is the average peak sun hours of the study area. Using the data obtained from the world weather and climate information [21], the average amount of sun hours of the study area is 2,452 hours a year equivalent to 6.6 sun hours per day.

Equation (4) evaluated using the average sun hours and the values in Table I and the module output power is 66.7 W. Therefore, a standard PV module rating of 90 W is required. Yingli solar 90 W panel selected for the study. The electrical characteristics of the panel at standard test condition (STC) given in Table II.

Table- I: Load consumption

Loads	Power rating (W}	Quantity	Use/day (hours)	Daily load (kWh)
Load 1	28	1	8	0.224
Load 2	18	1	8	0.144
Load 3	9	1	8	0.072
Total	55			0.44

Table- II: Polycrystalline Yingli solar 90 W panel

Parameter	Specification
Power output	90.0 W
Open-circuit voltage	22.0 V
Voltage at maximum power point	17.8 V
Short-circuit current	5.44 A
Current at maximum power point	5.06 A
Temp coefficient	38%
Module efficiency	13.5%
Panel dimension	1010mmx660mmx25mm
Warranty	25 years

3) Battery Sizing

The battery capacity should be adequate to store excess generation, meet the daily peak demand and supply power for a number of autonomous days on poor weather. The battery life depends on the system voltage, its Depth of Discharge (DoD), its efficiency and the total daily demand with the minimum battery capacity expressed as in [22].

$$C_B = E_D / \left(V \times DoD \times \eta \right) \quad (5)$$

where C_B denotes the minimum battery capacity in Ah, V is the DC operating voltage and η is the efficiency of the battery.

Taking the system DC operating voltage as 12 V, the DoD approximated at 80% and the battery efficiency taken to be 85%, (5) is evaluated and the battery capacity is 53.92 Ah thus a standard battery capacity size of 65 Ah is required. Yuasa NP65-12I, 12 V, 65 Ah lead acid battery chosen for the study.

4) Power Inverter Sizing

The losses associated with a power inverter are due to the voltage drop at the push-pull amplifier, which is the final transistor circuit thus, lowering the inverter output voltage. The inverter sizing is such that it is able to meet the maximum output power of the PV module. The total inverter power determined by using (6).

$$P_T = E_D / I_\eta \quad (6)$$

where P_T and I_η denote the total inverter power in watts and the inverter efficiency respectively. Equation (6) evaluated at average inverter efficiency of 80% and total load demand as in Table I to give inverter power as 66 W. Single phase Solarpex 150 W, 12 V DC to 230 V AC power inverter selected for the study.

5) Charge Controller Sizing

A charge controller is a switching device that protects the battery from overcharge and over discharge. Equation (7) gives the total current through the charge controller considering a safety factor of 1.25.

$$I = I_{SC} \times 1.25 \quad (7)$$

where I and I_{SC} denote the total current and the short circuit current in amperes of the selected PV module respectively. Equation (7) evaluated using parameters in Table II and the total current is 6.8 A. Solarmax battery intelligent 10A charge controller chosen for the study.

C. Energy Management Strategy

Experimental set up developed to demonstrate the real-time energy management of the microgrid. In the proposed energy management system (EMS), either the solar PV system or the national utility grid electricity supplied the load. A number of tasks carried out for accurately conducting the energy management system.

The first one being monitoring the flow of current to and from the battery bank. The second is measuring the battery state of charge, conducting logical decision making process integrating the PV module and the battery bank to the external utility grid and the last one being synchronization of the renewable energy sources with the utility grid with respect to voltage and frequency. These processes require complex electronic circuitry utilizing microprocessor circuit or a more intelligent computer to perform the energy management tasks that an analog electronic circuitry may not handle.

The proposed EMS is such that solar PV becomes the primary source of electric supply to the load; the excess PV power charges the battery through the charge controller. With a drop in solar irradiance, the battery bank (if full) supplies the load and with a further decrease in battery current beyond a specified limit, the load is suppled from the state electricity grid, which is the backup source.

The prototype uses Arduino Uno microcontroller to switch between the solar PV system and the utility grid electricity, the thresh hold limits specified by the energy flow algorithm in Fig. 3.

The load management system uses sensors to measure the flow of currents and display them on an LCD display for monitoring. The relay interface boards connect the load to the two sources of supply. The proposed energy management in the solar PV microgrid shown in Fig. 2.

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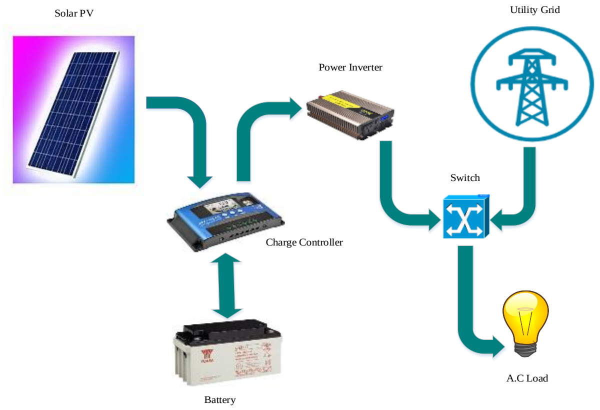

Fig. 2. Proposed energy management system

1) Hardware Components

Arduino Uno development board, voltage sensor detection module, 5 A current sensor ACS712, two 8-channel 240 V 10 A relay interface boards, 16x2 LCD display and LEDs are the main hardware players controlling the prototype.

2) Software Code

The initiation of the program starts with declaration of variables i.e. the sensors and the modules used in the study. Module/sensor is assigned digital or analog pin from the microcontroller i.e. int solarlive1=2. Here relay 1 which controls load_1 is connected to digital pin 2 of the microcontroller.

In the proposed energy management strategy, three loads represented as load_1, load_2, and load_3. Each load utilizes four-channel relay, two for PV system and two for utility grid. Relays for load_1 are labeled as solarlive1; solarneutral1; gridlive11; gridneutral11. Load_2 and_3 follow the same naming code and sequence. Variables and pin modes (input, output, and start using libraries) are initialized by calling the setup () function.

The bulk of Arduino sketch executed in the void loop (). The loop () function runs repeatedly until the microcontroller is reset. The void loop contains logical statements used by the microcontroller to determine the set conditions for loads isolation. From the energy flow algorithm given in Fig. 3, the conditions are the values of voltage and current from the voltage and current sensors e.g. if (current >0.12 &&current <0.22) { relays 1, 2, 7, 8, 11 and 12 are HIGH and relays 3, 4, 5, 6, 9 and 10 are LOW. This disconnects load_1 from the PV system reconnecting it to utility grid electricity.

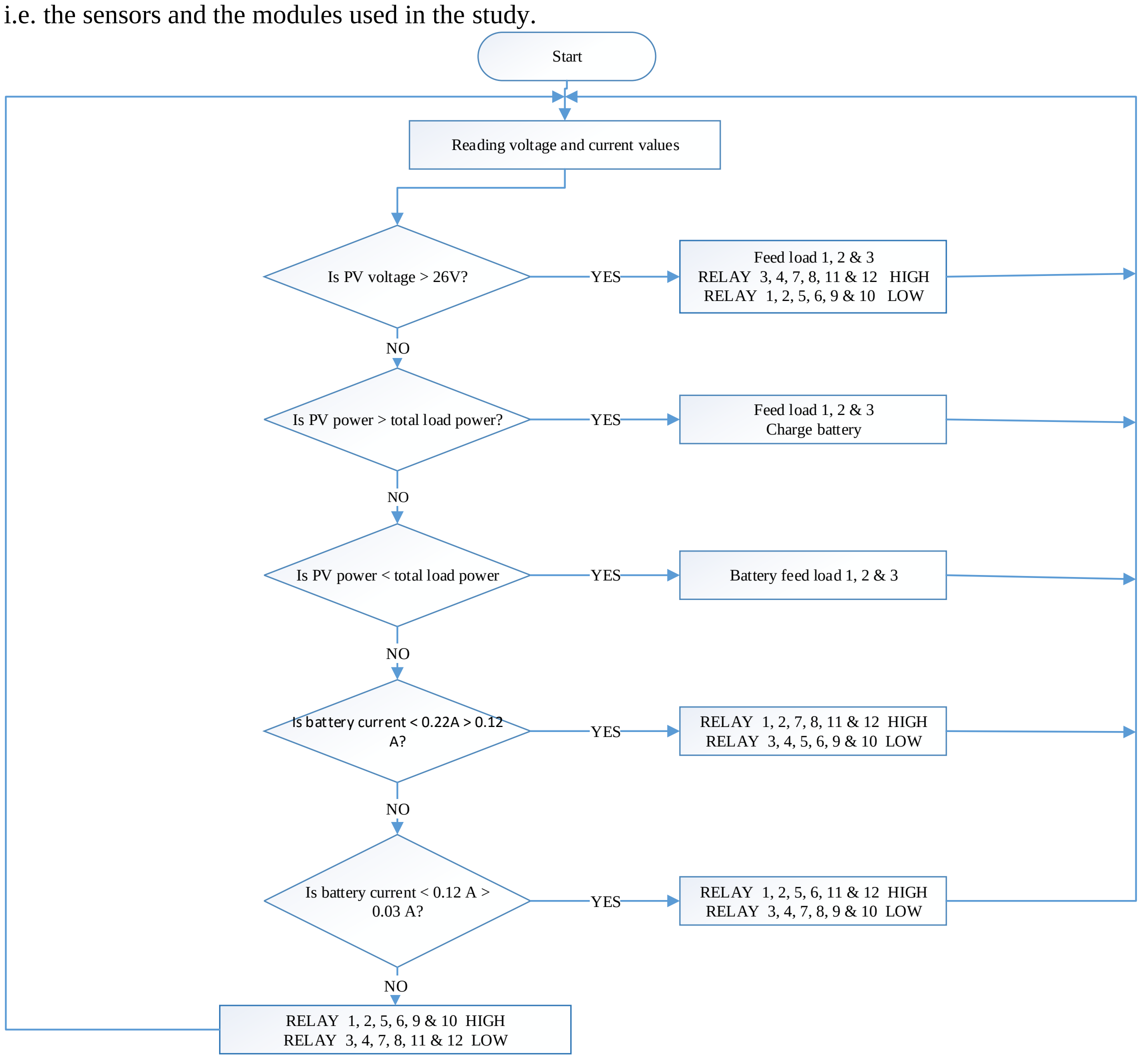

Fig. 3. Energy flow algorithm

D. Insolation

The amount of solar energy incident on a specified area for a specified time referred to as insolation or in other words the amount of solar energy hitting a specific area in a day. The effect of the solar insolation on a solar PV module generates electric power from the module given by (8).

$$E_g = G \times \eta P_V \times A \quad (8)$$

where E_g denotes the power generated by the solar PV module in Wh per day, G, ηPV, and A denote the solar irradiance in Wh/m^2 per day, the module efficiency and the module area respectively.

Medium term weather forecast covering a period of one year is possible using PVsyst photovoltaic software installed on a networked PC or a mobile device. Using the API toolkit, the user browses internet using the PC or a smart phone (having the application installed) at https://solcast.com in order to obtain short-term weather forecasts covering seven days ahead.

Solar irradiation data in both graphical and excel spreadsheet are obtainable in this software. Desired data variables for download include GHI, Direct normal irradiance (DNI), air temperature and cloud opacity.

E. Impact of Solar PV System Installation

Economic analysis of a project helps to ensure allocation of scarce resources efficiently and investment brings benefit to the developer.

1) Cost Analysis

The major goal of any investment is getting the most return on the investment by balancing the ratio between performance and cost.

The costs assigned to a particular component or part related to the PV project are termed "direct capital costs" whereas costs required for maintenance or servicing the installed PV system are the "operation and maintenance costs". Equation (9) expresses the total cost of utility grid electricity for a specified period without using solar PV system connection.

$$C_{grid} = E_D C_{units} \times 365T \quad (9)$$

where C_{grid} is the total cost of utility grid electricity for the life time of the project in US$, E_D, C_{units}, and T are the energy demand in kWh per day, the unit cost of energy and the project lifetime in years respectively. Equation (10) expresses the total cost of a solar PV system accounting for the cost of installation, operation and maintenance.

$$C_{PVS} = C_{PV} + C_{inv} + C_{bat} + C_{cc} + C_{others} \quad (10)$$

where C_{PVS} is the total cost of the solar PV system with no subsidy, C_{PV}, C_{inv}, C_{bat}, and C_{cc} are the costs of PV module, power inverter, battery and charge controller respectively, whereas C_{others} are other costs arising from installation, Arduino and accessories, operation and maintenance of the PV system. Table III gives the cost of components used in the study.

Table- III: Components and other cost estimates

Item Description	Quantity	Unit cost	Total US$
Yingli solar 90W panel	1	76.99	76.99
Yuasa 12V, 65Ah lead-acid battery	1	70.42	70.42
Solarpex 12 V/230 V inverter	1	19.37	19.37
Solarmax charge controller 10A	1	23.76	23.76
Arduino Uno & accessories	1	37.85	37.85
Engineering and labor costs	1	57.04	57.04
Total			286

2) Payback Period

The payback period is a measure of time (in years) the investment takes before it recovers its initial cost. The project becomes attractive when the payback period is shorter than the lifetime of the project. Payback period expressed as in [23].

$$PB = C_{PVS} / \left(E_D C_{units} \times 365\right) \quad (11)$$

where PB is the payback period in years.

3) Net Present Value

Net Present Value (NPV) is a financial analysis used to determine the value of an investment involving cash flow. It helps determine the worth of a project and accounts for the capital cost of investment, the cost of energy and the lifetime of the investment.

The investment is feasible and thus acceptable with a positive value of NPV, not acceptable when the NPV is negative. NPV of a project expressed as in [24].

$$NPV = -C_{Initial} + \sum_{t=1}^{N} \left\{ EC_t / \left(1+k\right)^t \right\} \quad (12)$$

where $C_{Initial}$ is the initial cost of investment of the solar PV system, EC_t is the energy cost for year t in US$, N is the total project duration period in years, k and t are the discount rate and the year variable in each summation respectively

IV. RESULTS AND DISCUSSION

A. Simulation Results

Energy sources were a solar PV system and the utility grid electricity. The solar PV system consisted of a PV module and a battery storage system both having DC output voltage converted to AC before supplied to the loads.

The storage battery absorbed surplus power from the solar PV module and provided additional load power on shortage from the PV module.

The model of Fig. 1 simulated in MATLAB/Simulink software with configuration solver parameter set to "discrete" at average irradiance and temperature of 552 W/m^2 and 24.32 °C respectively. The parameters determined by averaging the API 7-day forecast. Simulation results of power_load, power_PV, power_grid, and battery SOC shown in Fig. 4.

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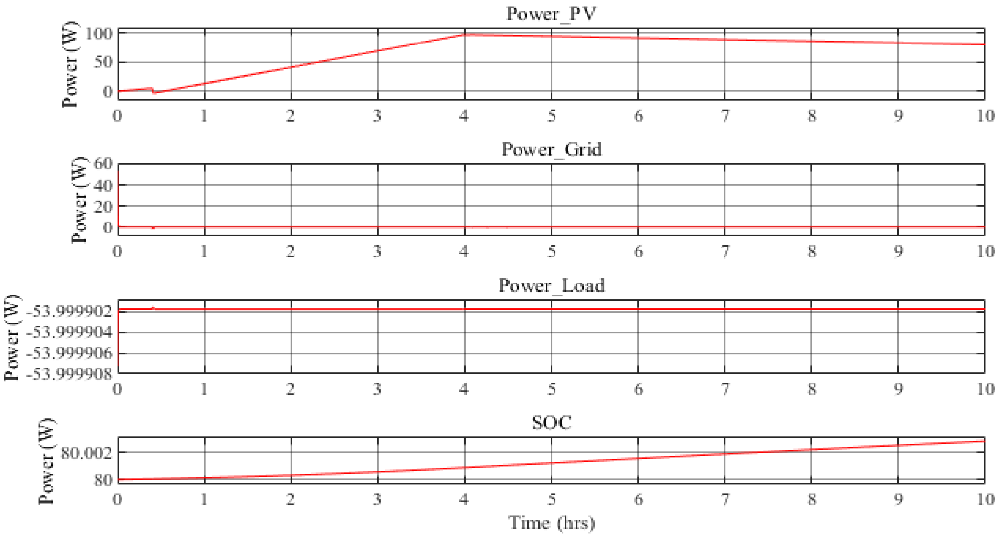

Fig. 4. Simulation results of power_load, power_PV, power_grid, and battery SOC

From the figure, power generation rose gradually from zero watt at 0h and attained the maximum power of 93 W at the fourth hour, beyond which it only dropped slightly. The solar PV panel supplied a total load of 54 W and at the same time charged the battery within the 10h period, meanwhile the grid power remained at zero watt for the stated time.

B. Real-time Results

The prototype assembled and the loads operated over a 24-hour period for better analysis of the proposed EMS. Fig. 5 shows the assembled prototype for the proposed system.

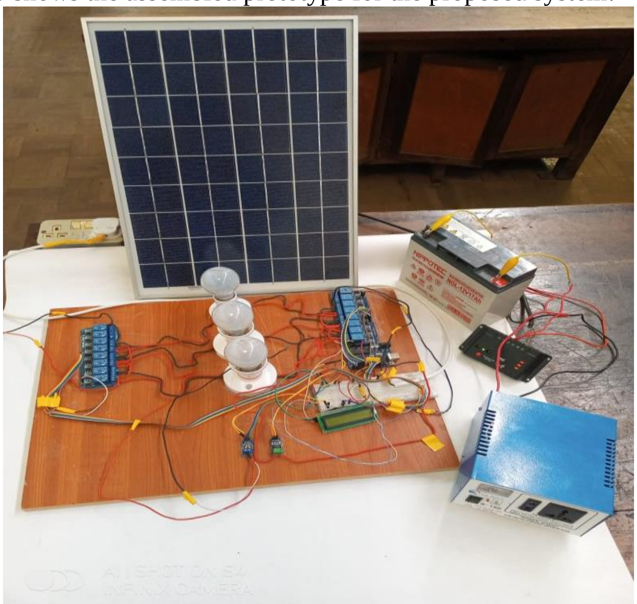

Fig. 5. Snapshot of assembled hardware components

The prototype is disconnecting the loads one at a time whenever the supply current from the micro sources becomes less than the specified threshold value. The load with the highest current demand disconnected first. After the disconnection, the relay reconnects the particular load to the utility grid electricity.

The 12 channel LCD displays the state of the loads at a given time; whether some loads are operating on solar PV system or on utility grid electricity. After total isolation of loads from the solar PV system source to utility grid electricity, 'CONFIGURATING' is displayed on the LCD screen. This means that the microcontroller is checking the status of PV module open circuit voltage if restored in order to switch the loads back to the priority power source. The current sensor always gave out current values above 0.1 A even when there is no supply from the PV system. This value used to set the microcontroller to switch off all the loads from the PV system to the utility grid allowing for repair or servicing.

C. Weather Forecasting Results

The results of the Mateo monthly computations collected by PVsyst photovoltaic software around the study area (Nairobi) for the year 2021 shown in Fig. 6. From the figure, the GHI of the study area shows that solar irradiance attained its peak value of 6.7 kWh/m^2 in February then starts to drop. July recorded the minimum solar irradiation of 3.8 kWh/m^2. Equation (8) evaluated using values in Table II, the maximum energy generated from the solar PV module during the month of February is 18.0 kWh, and July is 10.2 kWh.

Forecasts generally predict what is likely to occur. The prediction contains uncertainty due to the chaotic nature of the atmosphere. The Solcast's probability around the median forecast is 10% and 90% represented as P10/P90 in Fig 7. The data represented in the figure were obtained from the API live and forecast of the study area taken on 15th February 2022 at local time zone, Nairobi 2022-02-15T13:30:00Z. The results show that there were thin clouds persisting reducing the intensity of sunlight at the time of forecast specified. The API weather parameters in the study site for the six days forecast shown in Table IV.

Table- IV: API 7-day forecast

Date	Daily GHI (Wh/m^2)	Average GHI (W/m^2)	Temperature °C
2/16/2022	7,308	609.00	24.67
2/17/2022	7,507	625.58	25.00
2/18/2022	6,220	518.25	24.08
2/19/2022	5,536	461.33	24.00
2/20/2022	6,506	542.20	24.83
2/21/2022	5,375	447.92	23.42

The GHI is maximum at 7,308 Wh/m^2 per day on 16th February and minimum at 5,375 Wh/m^2 on 21st February.

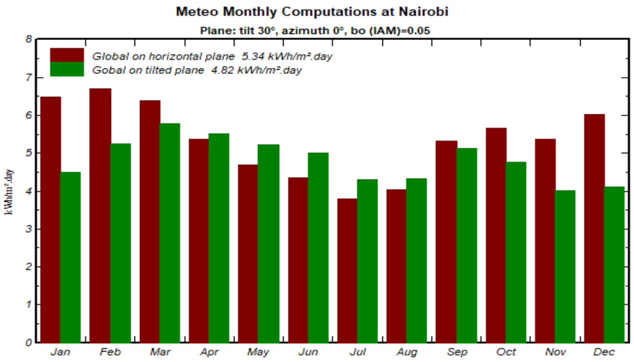

Fig. 6. Monthly Global solar irradiance (Nairobi)

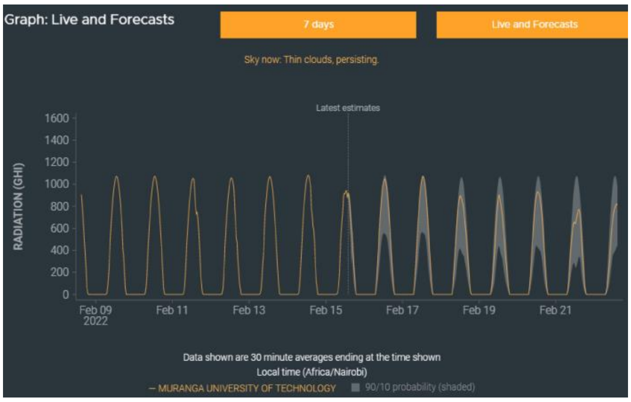

Fig. 7. API forecast (Nairobi)

Equation (8) is evaluated using the values in Fig. 7 and Table IV to give expected maximum power that can be generated from the PV module on 16th February as 657 Wh and on 21st February as 478 Wh respectively.

D. Economic Benefits

The cost of electricity for a household tariff is US$ 0.217 per kWh. For a constant daily demand of 0.44 kWh per day, the total cost of grid electricity for 25 years evaluated by (9) is US$ 870. Using the warranty period of 10 years, the lead acid battery replaced twice replaced. Other system components can operate for the whole life span of the project. The operation and maintenance industry rates taken as 10% of investment cost ≈ US$ 28.6 from Table III. The total cost of investing in the solar PV system with no subsidy evaluated by (10) using the values in Table III is US$ 384. The overall profit gained by switching from the utility grid to PV system for 25 years is US$ 486. Taking the total cost of investment as US$ 384, energy demand as 0.44 kWh per day and unit cost of energy as US$ 0.217 per kWh, (11) evaluated to give payback period of 11 years. For the 25-year warranty period of the solar PV module, the net present value evaluated by (12) is US$ 119.

E. Environmental Impact

The Energy and Petroleum Regulatory Authority (EPRA) in Kenya estimated the net grid emission factor for power plants in 2018 (still in force) at 0.3322 kg of CO_2 per kWh of energy generated [25]. Equation (13) evaluates the reduction of CO_2 emission by shifting production of electricity from fossil fuel to renewable energy sources.

$$CO_2\left(Emss\right) = E_D \times 0.3322 \times 365 \times 25 \qquad (13)$$

where $CO_2(Emss)$ is the amount of carbon dioxide emissions in kg/kWh and E_D is the energy demand in kWh per day. Equation (13) evaluated and the energy management achieved through switching between PV based microgrid and the utility grid is able to reduce 1,333.78 kg of CO_2 emissions during the 25 years of the project life.

V. CONCLUSION AND FUTURE WORK

This paper discussed modeling, real-time energy management and a weather forecast of a grid-connected solar PV system. Additionally, the economic and environmental impact of installing the solar PV system analyzed. The investment has a payback period of 11 years with an estimated net present value of $ 119 for the 25-year period. Experimental setup with Arduino board made and weather forecast using web interface enabled prediction of future power generation with the installed PV system. The forecast results proved useful in modifying the consumer usage in the next coming year on a medium or short-term basis assuming no adverse changes in weather pattern expected in this particular geographical region. The API software is a new technology recommended for further implementation in the field of renewable energy since it has many other parameters useful to such studies. The future work of this study is to predict consumer behavior using artificial intelligence like Neuro-Fuzzy and integrate it with the energy management studied for advanced output results.

REFERENCES

1. A. Kirbyshire and J. Graham, "United Nations Climate Change Conferences," 11 November 2021. [Online]. Available: https://www.c40.org/what-we-do/influencing-the-global-agenda/global-diplomacy-advocacy/united-nations-climate-change-conferences-cop/?gclid=EAIaIQobChMI9PWm-tq49gIVkACLCh0cHwXAEAAYASAAEgJybvD_BwE. [Accessed 17 November 2021].
2. A. G. Solanlk, S. Reddy and K. Kishore, "Modeling, Simulation and Performance Analysis of Solar PV System," International Journal for Modern Trends in Science and Technology, vol. 7, no. 9, pp. 264-272, 2021.
3. M. Palmer, S. Elliott and H. Jack, "Solar Irradiance Data," Solcast's, 06 February 2019. [Online]. Available: https://solcast.com/solar-data-api/solar-irradiance-data-everywhere-you-need-it/. [Accessed 27 July 2021].
4. IRENA, "International Renewable Energy Agency," 2022. [Online]. Available: https://www.irena.org/solar. [Accessed 03 January 2022].
5. A. Hota, S. K. Bhuyan and P. K. Hota, "Modeling & Simulation of Photovoltaic System Connected to Grid using Matlab," in ICREISG, Bhubaneswar, 2020.
6. D. Chippada and D. Reddy, "Mathematical modeling and simulation of energy management in smart grid," International Journal of Smart Grid and Clean Energy, vol. 9, no. 4, pp. 746-755, 2020.
7. Muhardika and Syafii, "Design of arduino-based loading management system to improve continuity of solar power supply," Indonesian Journal of Electrical Engineering and Computer Science, vol. 20, no. 3, pp. 1677-1684, 2020.
8. A. Mujahid and M. S. Rehman, "Power-saving smart energy grid meter for blackout management," Journal of Applied Science and Engineering, vol. 24, no. 4, pp. 491-498, 2021.
9. K. C. Meje, L. Bokopane and K. Kusakana, "Real-time power dispatch in a standalone hybrid multisource distributed energy system using an Arduino board," Elsevier Ltd., Bloemfontein, South Africa, 2021.
10. Q. A. Alabdali and A. M. Nahhas, "Simulation Study of Grid Connected Photovoltaic System Using PVsyst Software: Analytical Study for Yanbu and Rabigh Regions in Saudi Arabia," American Journal of Energy Research, vol. 9, no. 1, pp. 30-44, 2021.
11. F. H. Faiz, R. Shakoor and A. Raheem, "Modeling and Analysis of 3MW Solar Photovoltaic Plant Using PVsyst at Islamia University of Bahawalpur, Pakistan," International Journal of Photoenergy, Hindawi, vol. 2021, pp. 1-14, 2021.

12. M. H. Chung, "Estimating Solar Insolation and Power Generation of Photovoltaic Systems Using Previous Day Weather Data," Advances in Civil Engineering, vol. 2020, pp. 1-12, 18 February 2020.
13. J. M. Bright, "Solcast: Validation of a satellite-derived solar irradiance dataset," Solar Energy, pp. 1-22, 04 August 2019.
14. H. Al Zoubi, Y. Al Khasawneh and W. Omar, "Design and feasibility study of an on grid photovoltaic system for green electrification of hotels: a case study of Cedars hotel," International Journal of Energy and Environmental Engineering, vol. 10, pp. 616-626, 2021.
15. P. Thanarak and K. Lhazom, "Economic Feasibility Analysis of Off-Grid PV Systems for Remote Settlements in Bhutan," International Journal of Energy Economics and Policy, vol. 11, no. 3, pp. 206-214, 2021.
16. Z. Šimi´, D. Topi´ and I. Crnogorac, "Method for Sizing of a PV System for Family Home Using Economic Indicators," energies, pp. 1-18, 27 July 2021.
17. EPA, "epa.gov/ghgemissions/overview-greenhouse-gase," United States Environmental Protection Agency, 19 November 2021. [Online]. Available: https://www.epa.gov/ghgemissions/overview-greenhouse-gases. [Accessed 17 March 2022].
18. M. Azaroual, M. Ouassaid and M. Maaroufi, "Optimum Energy Flow Management of a Grid-Tied PV-Wind-Battery System considering Cost, Reliability, and CO2 Emission," International Journal of Photoenergy, Hindawi, vol. 2021, pp. 1-20, 2021.
19. S. Jiang and Z. Song, "A review on the state of health estimation methods of lead-acid batteries," Journal of Power Sources, vol. 10, pp. 1-18, 2021.
20. S. Jiang and Z. Song, "A review on the state of health estimation methods of lead-acid batteries," Journal of Power Sources, vol. 10, pp. 1-18, 2021.
21. jan@weather-and-climate.com, "weather-and-climate.com," 2010-2022 World Weather & Climate Information, 2022. [Online]. Available: https://weather-and-climate.com/average-monthly-hours-Sunshine,muranga-ke,Kenya. [Accessed 03 January 2022].
22. B. Aboagye, S. Gyamfi, J. C. Puoza and M. Obeng, "Techno-economic Feasibility Analysis of Solar Photovoltaic System for Single Households in Peri-urban Areas Kumasi, Ghana," International Journal of Sustainable Energy Development, vol. 8, no. 1, pp. 392-404, 2020.
23. C. A. Hossain, N. Chowdhury and L. Michela, "System and Cost Analysis of Stand-Alone Solar Home System Applied to a Developing Country," sustainability, pp. 1-13, 6 March 2019.
24. F. Obeidat and I. Rahoma, "One Year Real Data Rooftop PV System Performance Analysis of a University Academic Campus," International Journal on Energy Conversion, vol. 9, no. 4, pp. 168-174, 2021.
25. P. R. Oimeke, "Energy & Petroleum Statistics Report 2019," EPRA Publication 2019, Nairobi, 2019.

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[1] R. A. Soumana, M. J. Saulo and C. M. Muriithi, "Enhanced Speed Control of Separately Excited DC Motor Using Fuzzy-Neural Networks Controller," 2022 4th International Conference on Smart Systems and Inventive Technology (ICSSIT), 2022, pp. 729-736, doi: 10.1109/ICSSIT53264.2022.9716556.
[2] Adetokun, B.B., Ojo, J.O. & Muriithi, C.M. Application of large-scale grid-connected solar photovoltaic system for voltage stability improvement of weak national grids. Sci Rep 11, 24526 (2021). https://doi.org/10.1038/s41598-021-04300-w.

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