Performance investigation of solar photovoltaic systems integrated with battery energy storage

Ali O. M. Maka*[a], Tariq Nawaz Chaudhary[b],

[a]The Libyan Centre for Research and Development of Saharian Communities, Murzuq, Libya.
[b] Mechanical Engineering Department, University of Engineering & Technology Lahore (RCET, Gujranwala), Pakistan.

*Corresponding author email: maca_2412@yahoo.co.uk ORCID: https://orcid.org/0000-0002-9005-1500

Abstract

Solar photovoltaic devices are a clean/sustainable energy resource used to generate electricity in the current era. Overall, the energy yielded from these devices is used to supply the electrical loads in order to meet energy needs. Any building can store electricity produced by renewable energy technology supplies through energy storage using a battery system. This study aims to determine the system's optimal performance characteristics within solar photovoltaic (PV) systems, including coupling the solar system/inverter and controller/battery storage (BS). This study builds a model using solar simulation in the 'system advisor model' programme, utilising a photovoltaic system with the integration of battery storage, which can improve energy efficiency. High-efficiency battery storage is needed for optimum performance and high reliability. To do so, an integrated model was created, including solar photovoltaics systems and battery storage. Energy storage (ES) is a challenge that must be carefully considered when investigating all energy system technologies. The results indicated that the overall system has an annual energy yield of approximately 1,353 kWh/kW and a performance ratio of 0,85. The high energy yield occurred during the summer, owing to more sunshine hours and the high magnitude of solar intensity. The ultimate finding proposes an optimisation framework to estimate/delineate the energy of generation/storage arrangement based on the power potential.

Keywords: Solar PV system; Battery storage; Performance behaviour; Inverter/controller; Integrated system.

Nomenclature

A_{module}	Area of the module	NREL	International Renewable Energy Laboratory
AC	Alternating Current	NSRDB	National Solar Radiation Database

BS	Batteries Storage	P	Power (W)
$B_{current}$	Battery current (A)	P_{in}	Power input supplied (W)
$B_{voltage}$	Battery voltage (V)	P_{out}	Power output delivered (W)
B_{rating}	Battery rating	PV	Photovoltaic
BIPV	Building Integrated Photovoltaic	$P_{battery}$	Power of the battery
DNI	Direct Normal Irradiance	PVP_{out}	Photovoltaic Power output
DoD	Depth of Discharge	$P_{desired}$	Power desired
DC	Direct Current	Q	Quantity of electricity the battery delivers,
ES	Energy Storage	Q_o	Initial Battery Charge
$E_{Capacity}$	Energy capacity	Q_{max}	Battery's maximum charge
E_{Input}	Energy input	PR	Performance Ratio
E_{Output}	Energy output	STC	Standard Test Conditions
$E_{radiation}$	average yearly solar radiation	SAM	System Advisor Model
$E_{production}$	Energy production	SoC	State of Charge
F	Faraday constant	T	Temperature °C
G	Global solar intensity	T_{Cell}	Cell temperature °C
GHI	Global Horizontal Irradiance	T_{amb}	Ambient Temperature °C
GPS	Global Position System	TMY	Typical Metrological Year
I	Current (A)	V	Voltage (V)
I_o	dark current density (A)	VDC	Voltage Direct Current
I_L	Light generated current (A)	Y_{module}	Yield module power
$INV_{control}$	Inverter control	**Greek letters**	
Li-ion	Lithium-ion	n	diode ideality factor (–)
LAB	Lead-Acid Battery	k	Boltzmann constant (eV/K)
CL	Cyclic life	q	Electron charge (c)
MPP	Maximum Power Point	$\eta_{battery}$	Battery efficiency
MPPT	Maximum PowerPoint Tricker	$\eta_{invertor}$	Inverter efficiency
N	Number of moles of materials	η_{system}	System efficiency
NOCT	Nominal Operating Cell Temperature.	η_{module}	Module efficiency

1. Introduction

Currently, conventional fossil fuels such as oil, coal, and gas are used extensively as a primary energy source. Fossil fuels contribute approximately 66% of global carbon dioxide emissions and greenhouse gases [1]. There has been an acceleration in the demand for environmentally friendly energy, which has ultimately resulted in a substantial decrease in energy costs globally [2, 3]. According to the Paris Climate Agreement, it is necessary for future generations and the present to achieve a much more stable and secure environment. Leaders of 197 countries have agreed to work/cooperate on decreasing greenhouse gas emissions and increasing resilience to the consequences of global warming [4, 5].

Renewable energy technology has become the most demanded energy resource due to its sustainability and environmentally friendly energy [6, 7]. In addition, renewable technologies are developed, which are cost-effective and attractive supply for electricity generation [8, 9]. Among the many renewable energy resources is solar energy application technology came in the forefront, which has a vast deployment and installation worldwide [10]. Therefore, it is essential to depend more on the systems of solar energy technology, which is abundant, sustainable and renewable, due to the significant energy needs of the world [1, 11]. Since progress has increased significantly in the past few decades, solar photovoltaic technology has become possible in meeting all of the world's energy needs [12-14].

Energy storage captures energy produced in a given period for usage at another time; hence, it reduces fluctuations between energy production and energy demand [15]. Energy shortages mostly occur due to fluctuations in weather conditions, which greatly influence the amount of energy produced. Although they result in financial losses, excess and shortage cases are interpreted as losses [16]. Energy storage systems are frequently presented as a practical economic solution to reduce losses and prevent the limitation of the generated electricity if it is not required. It can simultaneously increase the building's resilience while reducing energy losses [16, 17].

Batteries are key for photovoltaic systems that provide a steady and dependable power source and are used as an energy supply during night or cloudy days [18-20]. Battery lifespan, attainable power, maintenance requirements and efficiency are essential battery characteristics that influence the operation and performance of a solar system [15, 21]. An optimum battery has affordable prices, great effectiveness, a high density of energy, and the capacity to be discharged and charged indefinitely under arbitrary charging and discharge cycles [21].

In the literature, many papers have attempted to study various perspectives of solar PV with battery systems. Li et al.[22] performed and explained the most effective solar photovoltaic (PV) system designs for energy storage systems incorporating batteries. Overall, by presenting and employing an algorithm of dynamic programming, this comprises a lengthy time horizon involving the battery-assisted photovoltaic systems' entire life cycles. Research conducted by Chadly et al.[23] simulated techno-economic energy storage systems utilising Li-ion batteries solid oxide fuel cells. The findings demonstrate that factors such as round-trip efficiency, installation factors and capital outlay, particularly capital expenses, can significantly impact the expense of energy storage systems. Elazab et al.[24] investigated a smart home energy management model based on the most prevalent residential tariff used in developing countries. The assessment included load shifting, air conditioning and vehicle-to-home decrease. Mudgal et al.[25] proposed a hybrid wind, bio-battery and photovoltaic systems model and incorporation with phase change material. The consequence of that model is photovoltaic module performance effectiveness rises, which reduces overall system cost. Iqbal and Dabas [26] performed a dynamic model of a photovoltaic battery system in MATLAB/Simulink. In contrast to the diesel generator, with a PV-battery system option, an isolated photovoltaic-battery system is a more cost-effective way to supply residential loads.

A study induced by Mirletz and Guittet [27] focused on photovoltaic and load profile estimates with an emerging algorithm that signified price signals dispatch and automated the economic dispatch of PV-battery systems. The system advisor model (SAM) tool evaluates and integrates this method. Since a balance between demand cost management and signals dispatch is required, signals dispatch outperforms the SAM's algorithms. Wang et al.[28] compared energy management strategies of on-grid solar PV-battery systems for buildings and outlined the findings that building and photovoltaic-battery energy storage systems indicate that the technique is viable. Borkowski et al.[29] proposed a photovoltaic energy management strategy and a combination of a further control mode to enhance the system's profitability. The modification enables the creation of an estimation of performance degradation that depends on the battery's end of life. The cost profile indicated an increased energy storage profit rate in the connected photovoltaic management mode. Behmann et al. [30] studied various designs for integrating the battery into the micro-photovoltaic system. Thus, battery and photovoltaic modules have a parallel electrical link in a passive hybrid structure. The deduction from the experimental results shows that both active and passive coupled architectures are feasible. Hammami et al.[31] propose an analysis of a system incorporating solar modules with batteries to store electric energy by developing models to assess the temperature rise of the solar module and batteries under different conditions. It explains the increasing cell battery temperature and the impact of reduced thermal exchanges on the back of the PV module. Nkuriyingoma et al.[32] conducted a techno-economic study on a grid-connected solar PV system with a battery energy storage system (BESS) at a small house in Rwanda. PV*SOL software tool was used to simulate and assess the feasibility of integrating BESS. The study was technically and economically viable for addressing the issue of electrical power outages in developing countries.

Therefore, based on the literature studies in references [22-32], most of these research efforts have focused on the systems of PV-battery performance. Thus, they have generally neglected systems working in harsh surrounding conditions and which don’t adopt tangible integration scope with energy management. This research covers the system exertion when integrating a solar photovoltaics system with battery storage to operate in harsh environments, such as the desert. Thus, it is important to understand performance behaviour to implement better and exploit natural resources. The significance of this work can contribute insights for assessing substantial performance components of solar PV systems for developing research and innovation. This work aims to ensure the optimal performance of solar photovoltaic systems, encompassing coupling solar system/inverter and controller/battery storage. The remainder of this paper is organised as follows: Summarised in the general introduction in Section 1. The proposed method and the mathematical modelling are described in Section 2. The results and discussions included the solar PV, battery, and inverter in Section 3. The presentation of the integration of the energy system in Section 4. The key outcomes and conclusions of this study are summarised in Section 5 and include an overview of the plan for the next research.

2. Methods

This section highlights the approach based on the integrated system model followed by a mathematical model. This study uses a modelling approach to predict the performance of solar PV integrated with battery storage. The engineering software so-called ‘system advisor model’ established by (NREL), is used to build the model. Additionally, the mathematical model is applied; thus, the mathematical model is based on a set of mathematical equations.

2.1. Integrated Model

In this study, we proposed a model containing a solar photovoltaic array connected to a building to supply electricity. This system uses solar PV devices during diurnal hours and an integrated high-efficiency battery system in the evening or during cloud cover fluctuations. The energy produced from PV arrays flows to the inverter and is then supplied to the load. The inverter/controller charges the batteries' bank during the daytime, although during the batteries' use, the power outflow to the inverter subsequently supplies the load. Fig.1 illustrates a schematic of the solar photovoltaic and battery storage integration system.

The model is designed to provide electricity to power buildings under environmental conditions in Sabha city, located in the southwest region of Libya. According to the global position system (GPS), the study district is located southwest of its coordinates, with a longitude of 14,4° E, latitude of 27,03° N and altitude of 429m. The weather data file of the typical metrological year (TMY) of the solar resource library uses a programme called the system advisor model (SAM), a software package developed by the International Renewable Energy Laboratory (NREL) in the USA. A comprehensive model was built into the SAM to understand the operating performance of the integrated system. The tools used in this study are characterised by their powerful capabilities, accessibility, and accurate software.

The load energy profile is considered in this study. The energy management system will provide more energy in the case of high energy needs, depending on the demand. Therefore, the battery storage system will provide energy to load and work as a pick-up to compensate for the energy demand.

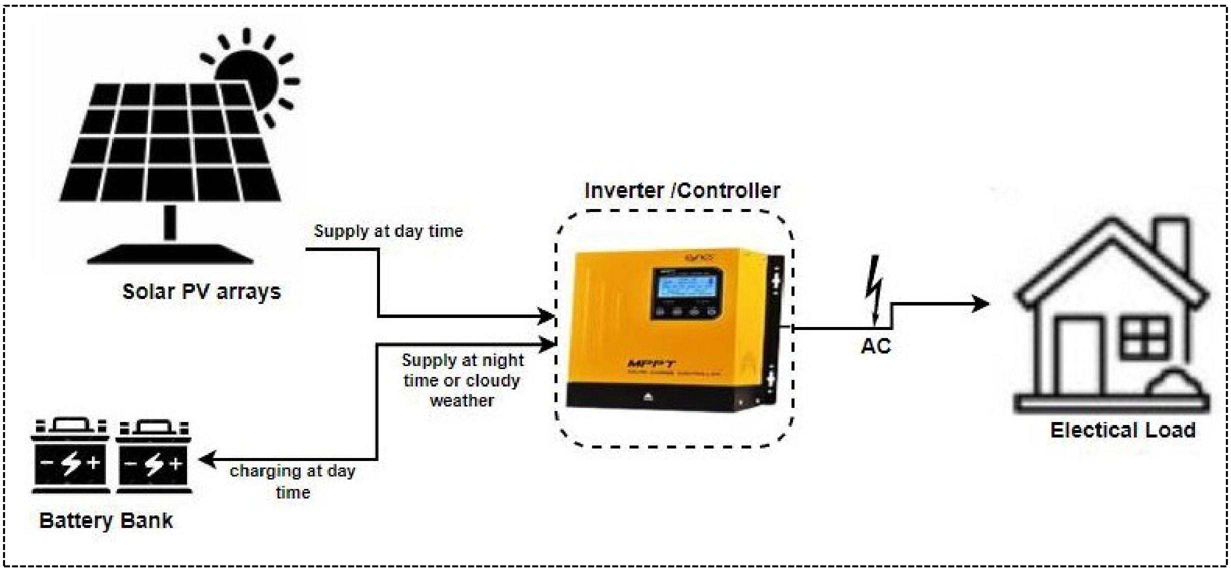


Fig.1 Schematic flow of integration system of solar photovoltaic and battery storage.

2.2. Mathematical modelling

2.2.1. Solar PV

A simple photovoltaic system model considers all the parameters of the efficiency of photovoltaic power generation. Additional models are based on single- and double-diode modelling key performance parameters. Under standard test conditions (STC) parameters, the solar PV module can potentially be employed to create an exemplary photovoltaic framework. In addition, the maximum power point (MPP) approach is often ascertained to yield the best photovoltaic power output. The following equations (1-4) can be used to determine the efficiency of the solar PV module.

$$I = I_L - I_0[\, exp\, (\frac{qV}{nkT}) \tag{1}$$

$$V = \frac{nkT}{q}\, Ln\, (\frac{I_L}{I_0} + 1) \tag{2}$$

$$P = V.I \tag{3}$$

$$\eta_{module} = \frac{V.\ I}{G.\ A_{module}} \tag{4}$$

where (P) is the output power, (*I*) is the produced current, (V) is the produced voltage, (A_{module}) is the area of the PV module, and (G) is the global solar intensity. The performance of solar photovoltaic technology is significantly influenced by the distribution and intensity of solar radiation.

2.2.2. The Battery

Mainly storing electrical charge, a battery's key function is to store electrical energy, making energy storage an essential component. Factors such as battery efficiency, internal resistance, or discharge characteristics can affect a battery's power output. Battery power can be quantified using the following formula.

$$P_{battery} = B_{current}\ x\ B_{voltage} \tag{5}$$

where ($B_{current}$) is the battery current and ($B_{voltage}$) is the battery voltage. Equation (6-7) [33] is a simple equation that can be utilised to determine the energy capacity of battery storage.

$$E_{Capacity} = B_{rating\ (Ah)}\ x\ B_{Voltage} \tag{6}$$

where (B_{rating}) is the battery capacity rating (Ah), which represents the quantity of current that a battery can produce over a period of time in normal situations. The battery storage capacity rating is given by:

$$B_{rating} = N\ x\ F\ x\ {}^{1h}/_{3600\ sec} \tag{7}$$

where (N) is the number of moles of materials and (F) is the Faraday constant. The overall battery efficiency encompasses both voltage and columbic efficiency. The battery efficiency can be quantified by using equation (8).

$$\eta_{Battery} = \frac{E_{output}}{E_{input}} x\ 100 \tag{8}$$

where (E_{output}) is the energy delivered from the battery, and (E_{input}) represents the energy supplied to the battery.

2.2.3. Inverter

Maximum power point tracking (MPPT) optimises the operation of solar PV module arrays under varying environmental conditions. The key operating characteristics of MPPT include efficiency, response and stability, which all affect the system characteristics. The MPPT algorithm, control approach, configuration of the converter from DC to AC type, battery, photovoltaic array size, and energy management system. Equation (9) is an equation that can be utilised to determine the inverter efficiency.

$$\eta_{Inverter} = \frac{P_{output}}{P_{input}} x\ 100 \tag{9}$$

where (P_{output}) is the power output delivered by the inverter to the load, and (P_{input}) is the input power supplied to the inverter.

3. Results and Discussion

3.1. Solar PV System

The performance of a photovoltaic system is often influenced by incidence irradiance in the plane of the solar panels, incident light spectrum and solar cell temperature. Consequently, system performance alters according to the time of day, solar insolation, direction and tilt of the modules, cloud cover, soiling, shading, temperature, state of charge, day of the year and location.

The physical characteristics of PV devices are made from traditional solar mono-Si material. The number of cells is 96; all are linked together to represent one module, and a module has an area of approximately 1,631 m^2. The electrical configuration of the system is fixed, the installation tilt angle is approximately 30°, and the azimuth angle is about 180°.

Photovoltaic (PV) devices are described via the module (I-V) curve; since it is more involved with the overall voltage and current that the photovoltaic module produces. The graph represents the voltage and current under operating circumstances, as shown in Fig.2, this prototype's typical photovoltaic module (I-V) curve at standard test conditions (STC).

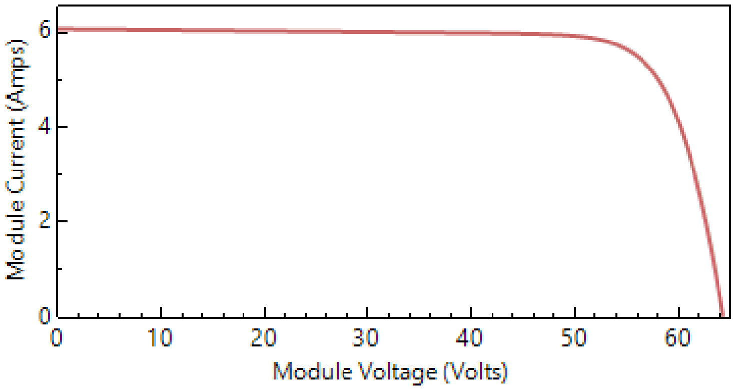


Fig.2. Typical solar photovoltaic module (I-V) curve at STC.

The solar PV device technology used in this study has been specified based on the dataset of manufacture given by “Solar Power SPR-E310-COM”. Accordingly, the results of the main parameters of solar photovoltaic module operating characteristics are listed in Table 1.

Table 1 Parameters of photovoltaic PV module operating characteristics.

Parameter	Nominal efficiency	Maximum power	Maximum voltage	Maximum current	Open circuit voltage	Short circuit current
Value	19%	310 WDc	54,7 VDc	5,7 ADc	64,4 VDc	6 ADc

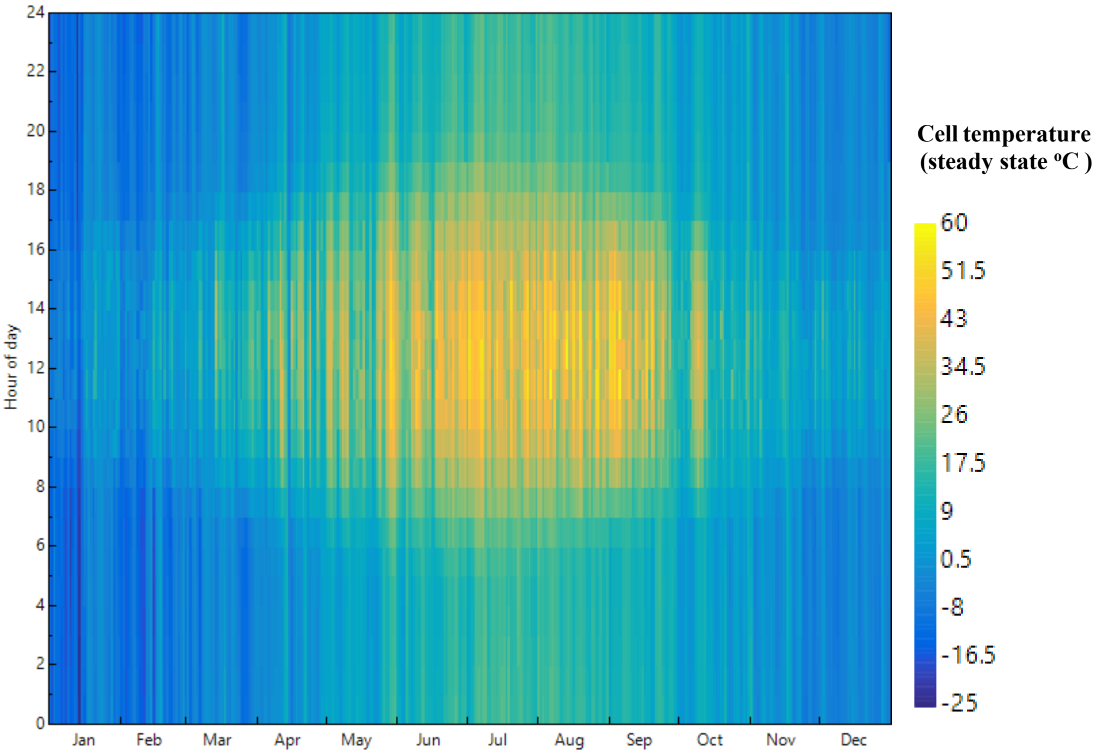


Fig.3. Estimation of solar photovoltaic cell temperature at a steady state.

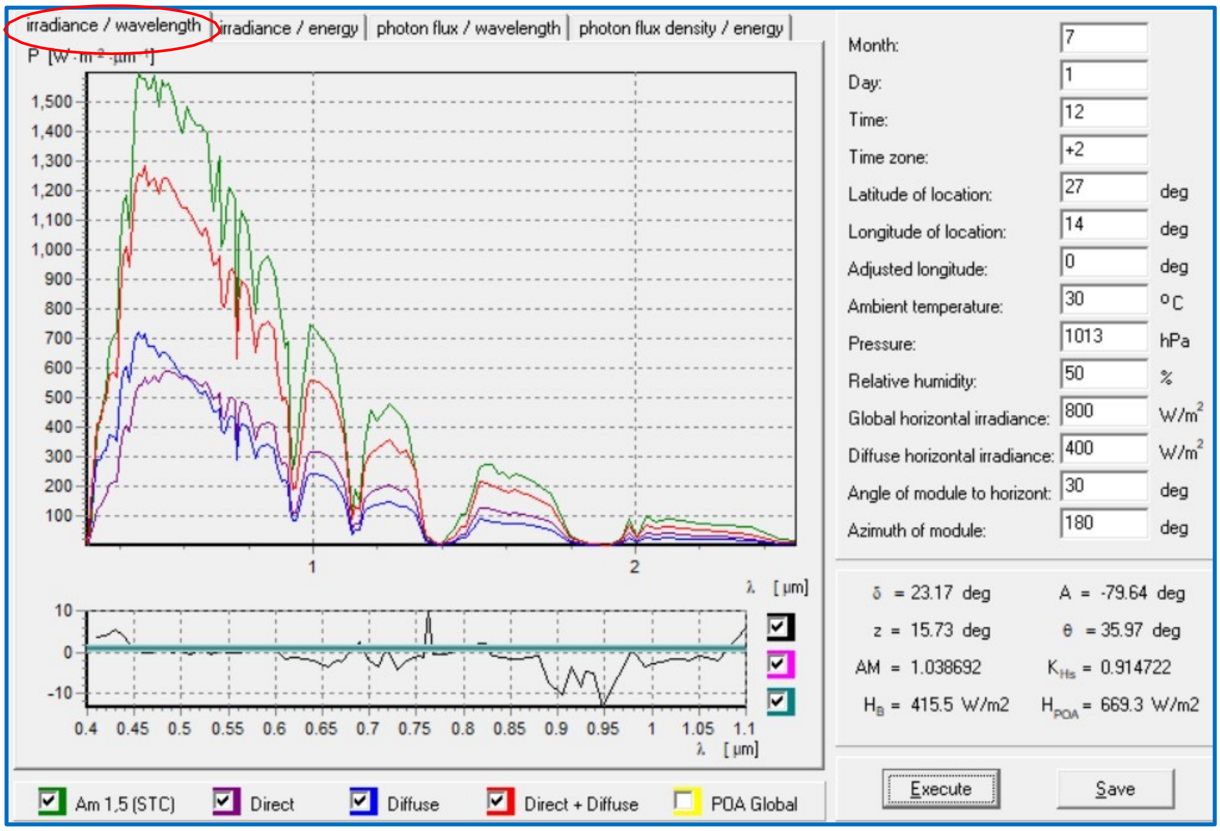
Solar cell/module is semiconductor devices which sensitive to temperature a rise. The temperature is a key parameter to consider when designing/installing any solar PV module system. The increase in the operating temperature results in an undesirable decrease in operating parameters for the open circuit's voltage, fill factor, output power, and efficiency. Conversely, the increase of short circuit current subsequently affects overall performance behaviour [34-36]. As shown in Fig.3, the steady-state cell temperature fluctuated over the year, but the high value was during the summer (from May-September), from 10 am to 4 pm. A solar PV cell is widely affected by the increase in temperature, which significantly affects performance behaviour. The heat-induced on the solar cell because some solar spectrum components don't convert to electricity, and will convert to heat and cause an environmental temperature factor. Thus, cell efficiency and other performance parameters decrease as the temperature increases. The expression (10) gives the ratio between the nominal temperature and the temperature of the module:

$$T_{cell(t)} = T_{amb} + \frac{NOCT-20}{800}\,.G \tag{10}$$

where (T_{amb}) represents the ambient temperature, (G) is the solar irradiation, (T_{cell}) is the cell temperature and (NOCT) is the nominal operating cell temperature.

The effectiveness of a solar energy system is subject to the environment, the equipment employed, and the system's installation. The ratio of actual photovoltaic (PV) output to expected values can be used to quantify PV performance, which is necessary for the efficient maintenance and operation of photovoltaic solar facilities. The global sunlight irradiance in the plane of the solar PV arrays, which comprises both direct and diffuse radiation, is the main energy source [37].

The solar spectrum is utilised to comprehend the Sun's composition, temperature, and other characteristics. Also, solar spectrum analysis is used to optimise the efficiency and design of solar cells in order to maximise energy capture. It describes how electromagnetic radiation from the Sun is dispersed throughout a broad spectrum of wavelengths. In general, a wide range of wavelengths are present in the solar spectrum, with visible light being the most well-known region. Fig.4 displays the solar spectrum prediction, which included air mass, direct, diffuse and (direct + diffuse) irradiance, where section (a) depicts the relationships of irradiance versus wavelength and section (b) irradiance versus energy. These estimated values were achieved using a solar spectrum program for that specific study area.

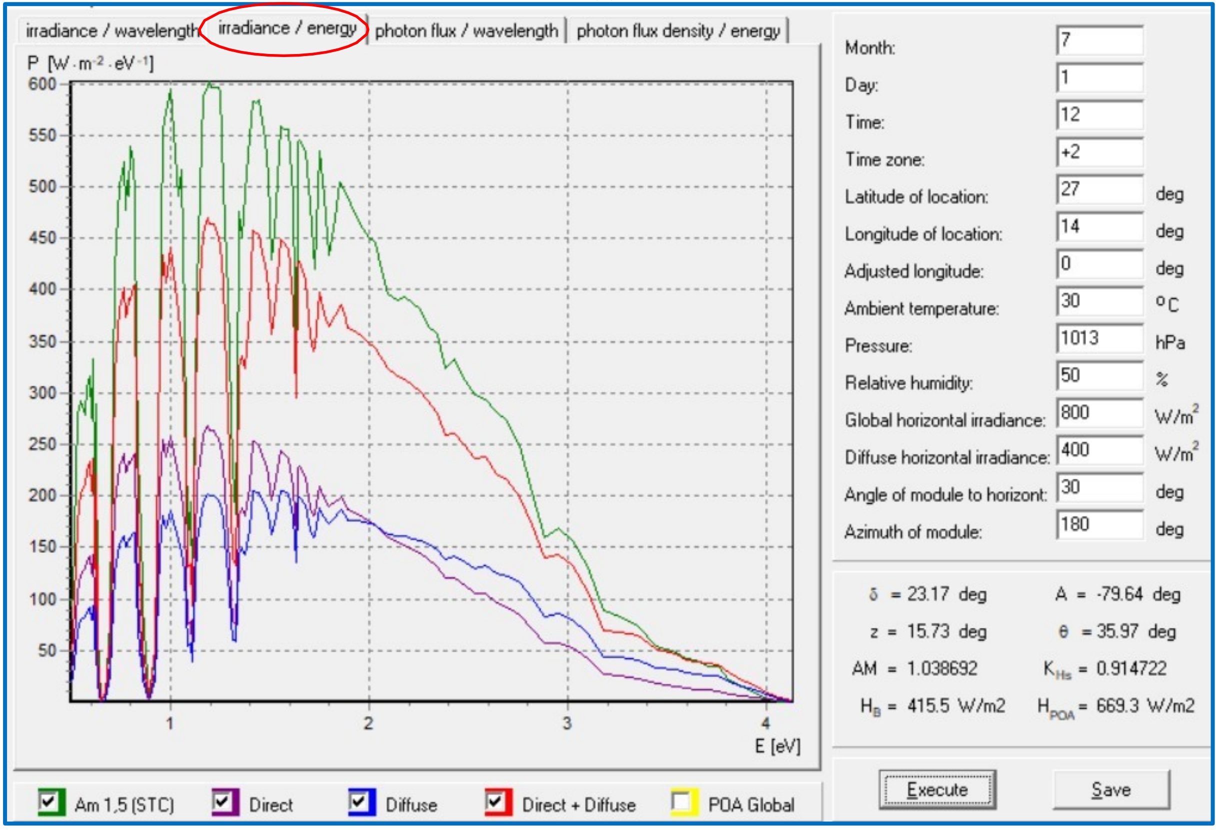


Month: 7
Day: 1
Time: 12
Time zone: +2
Latitude of location: 27 deg
Longitude of location: 14 deg
Adjusted longitude: 0 deg
Ambient temperature: 30 °C
Pressure: 1013 hPa
Relative humidity: 50 %
Global horizontal irradiance: 800 W/m^2
Diffuse horizontal irradiance: 400 W/m^2
Angle of module to horizont: 30 deg
Azimuth of module: 180 deg

δ = 23.17 deg A = -79.64 deg
z = 15.73 deg θ = 35.97 deg
AM = 1.038692 K_{Hs} = 0.914722
H_B = 415.5 W/m2 H_{POA} = 669.3 W/m2

☑ Am 1,5 (STC) ☑ Direct ☑ Diffuse ☑ Direct + Diffuse ☐ POA Global

(a)



Month: 7
Day: 1
Time: 12
Time zone: +2
Latitude of location: 27 deg
Longitude of location: 14 deg
Adjusted longitude: 0 deg
Ambient temperature: 30 °C
Pressure: 1013 hPa
Relative humidity: 50 %
Global horizontal irradiance: 800 W/m^2
Diffuse horizontal irradiance: 400 W/m^2
Angle of module to horizont: 30 deg
Azimuth of module: 180 deg

δ = 23.17 deg A = -79.64 deg
z = 15.73 deg θ = 35.97 deg
AM = 1.038692 K_{Hs} = 0.914722
H_B = 415.5 W/m2 H_{POA} = 669.3 W/m2

☑ Am 1,5 (STC) ☑ Direct ☑ Diffuse ☑ Direct + Diffuse ☐ POA Global

(b)

Fig.4. Prediction of solar spectrum irradiance (a) irradiance versus wavelength (b) solar irradiance versus energy.

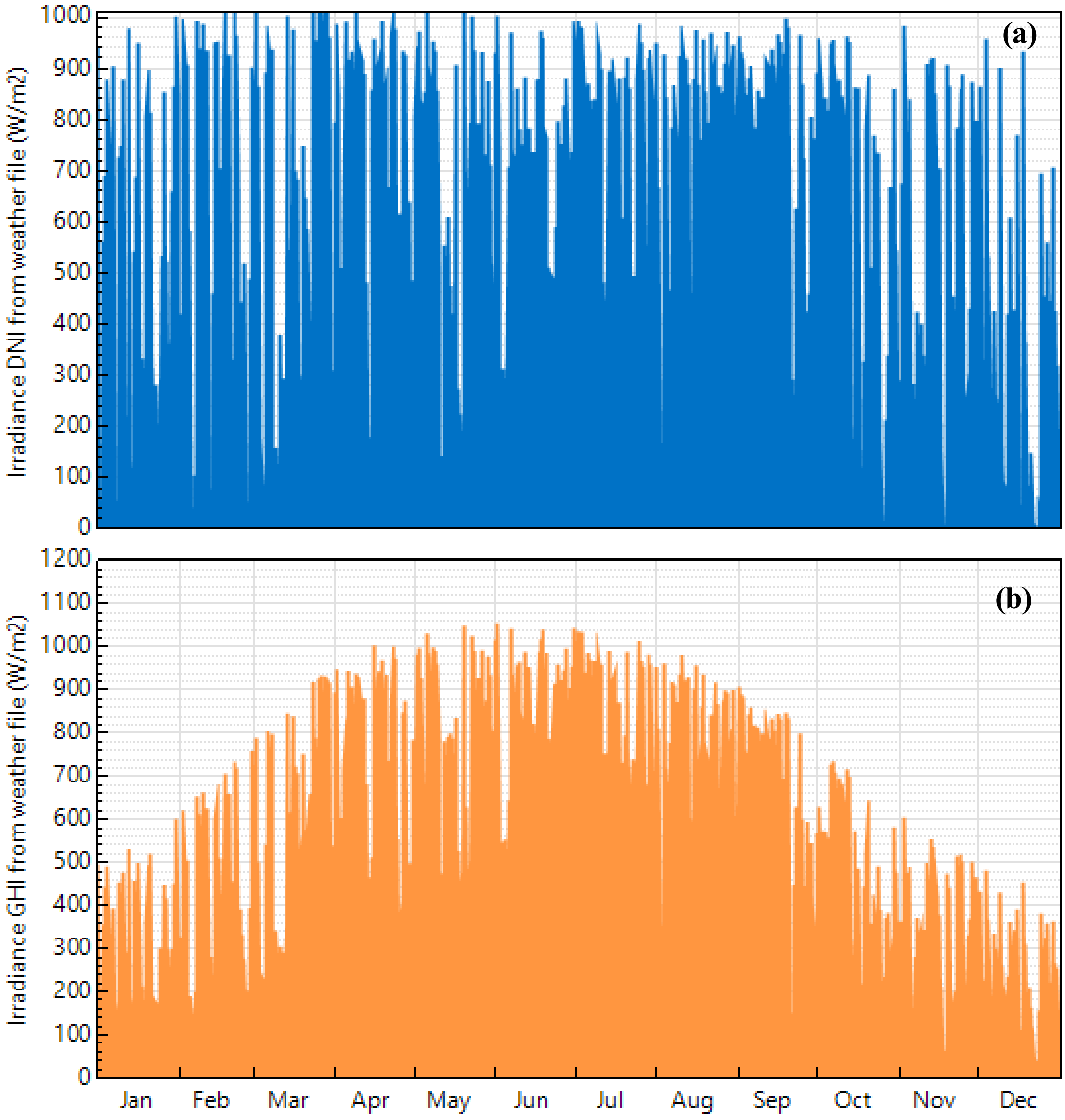


Fig.5 Potential of solar radiation in Sabha city (a) direct normal irradiance (DNI), section (b) global horizontal irradiance (GHI).

Solar PV modules' efficiency and output power rely widely on many solar radiation intensities, so it is significant to determine the installation site. The potential for solar radiation varies depending on the seasons, so the summer season has a high recorded potential. Many methods and databases are available that utilise historical data on the weather, satellite metrics, and modelling techniques to predict the solar radiation potential of a specific site. The weather data file of the typical metrological year (TMY) in which depends on the National Solar Radiation Database (NSRDB). Fig.5 (a) shows the fluctuation of DNI irradiance over the year; hence, the area study is rich and has high potential solar radiation. Also, section (b) displays global horizontal irradiance GHI potential, which averages 600 W/m^2.

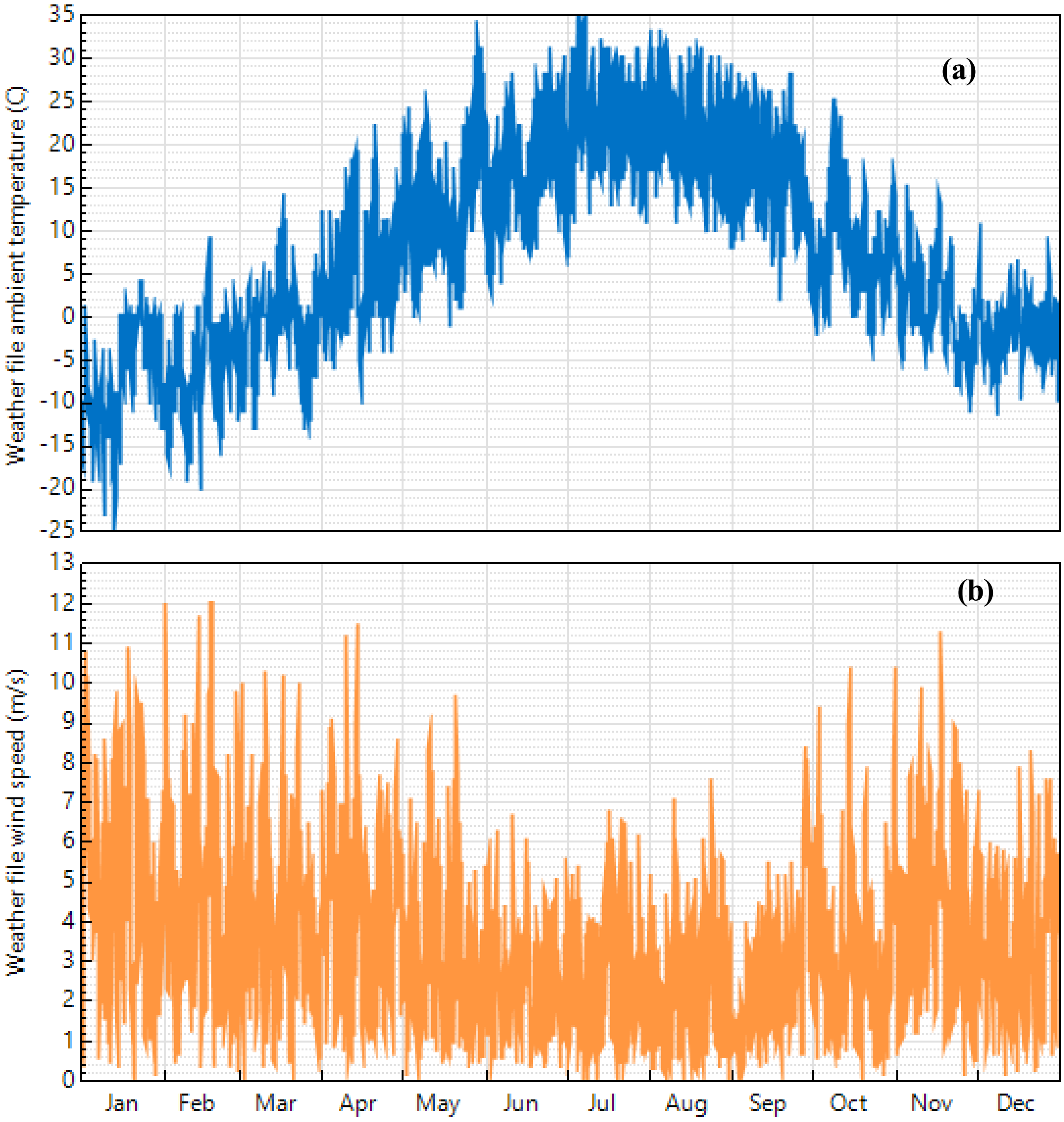


Fig.6. Yearly environmental metrological data, (a) the ambient temperature, and (b) wind speed.

It is important to understand the effects of wind and ambient temperature on the performance of solar PV systems. So, that is significant for optimising solar PV, designing, operating, and installing, guaranteeing long-term reliability, and ensuring high solar PV efficiency. There was a variance in ambient temperature from one season to another; thus, the higher ambient temperature was recorded during the summer, sometimes hitting 40 ºC. The wind speed also fluctuates, with the average wind being about 5 m/s. Fig.6. displays the annual environment metrological data of the current study area. The region's topography is important in determining its potential for solar intensity, ambient temperature and wind.

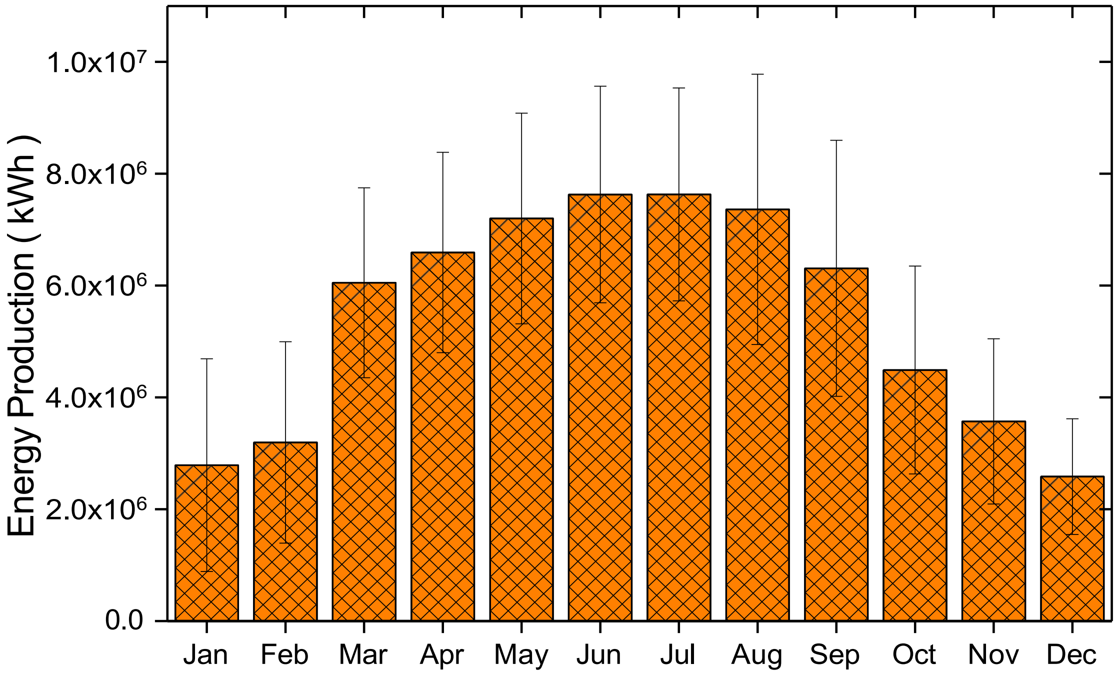


Fig.7. Estimation of monthly energy production.

Fig.7. estimates monthly energy production and elucidates that standard solar systems produce more energy during that time due to a significant amount of (DNI) available in the summer because the daytime has more illumination periods. In-vividly, the energy production showed that the system produced more energy in the summer because so much DNI was available. The approximation of annual solar photovoltaic energy production (kWh) can be predicted based on equation (11).

$$E_{production} = \int_{t1}^{8760} A_{module}\ x\ PR\ x\ Y_{module} x\ E_{rdiation} x\ dt \qquad (11)$$

where (PR) is the annual performance ratio, (A_{module}) is the area of the PV module (m^2), (Y_{module}) is the yield power of the module (%), and ($E_{radiation}$) is the average yearly solar radiation. The modelling results of the predictable energy yield over one year are presented. Table 2 lists the summaries of annual energy system metrics.

Table 2. Summarises the overall energy system metrics.

Annual energy (kWh)	Annual energy yield (kWh/kW)	Annual performance ratio	Annual capacity factor (%)
67,653,904	1,353	0,85	15,4

The efficiency is the key operating parameter of any device that is utilised to determine the optimal performance. The overall system efficiency can be determined using Eq. (12), which sums up the three components of the battery, PV module arrays and inverter system efficiency.

$$\eta_{system} = \eta_{PV,modules} + \eta_{Inverter} + \eta_{Battery} \tag{12}$$

3.2. Battery Storage

The battery is a device that shifts energy stores in the chemical bonds of a material into electrical energy [21]. Battery storage systems are also usually utilised to store the energy generated from other sources. The battery's efficiency is represented in the ratio of the total input to the total output of the storage system.

The number of discharging and charging cycles a battery can withstand before its capacity declines to 80% of its nominal value is known as its "cycle lifetime". The battery capacity is determined by the battery's quantity of charge or stored energy [21].

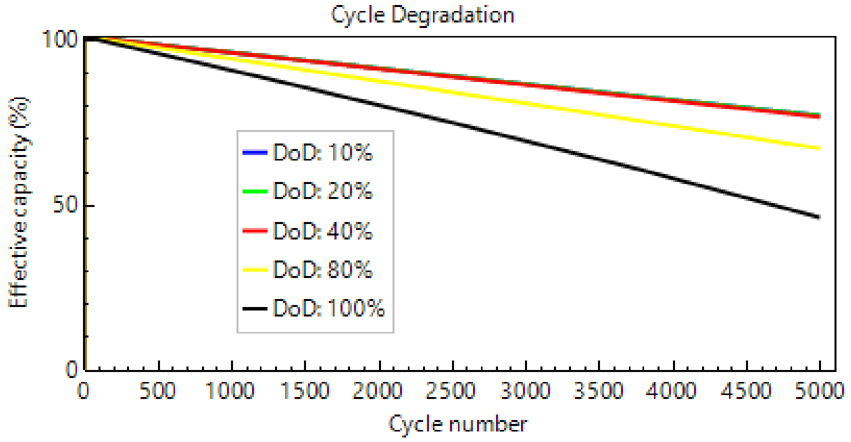


Fig.8. Cycle degradation of battery performance.

As shown in Fig.8, the cycle degradation of battery performance. The battery's number of cycles depends on the depth of discharge. In-vividly shown in the cycle lifetime and capacity increase with the increase of DoD. The high percentage of DoD 100% will degrade and decrease the effective capacity to approximately half versus the number of cycles at five thousand cycles. The 10-40% low DoD percentage only decreases the capacity to about 80%.

The battery capacity decreases as the number of charge and discharge cycles increases, according to the cycle degradation concept. In addition to cycle degradation, the choice of calendar degradation governs how capacity decreases over time, regardless of cycling.

Depth of discharge (DoD) estimates how much of the battery has been depleted in relation to its overall capacity. The quantity of charge/discharge cycles a battery undergoes during its useful life is called “cyclic life” (CL). The battery’s life can be increased by storing it in a cool environment.

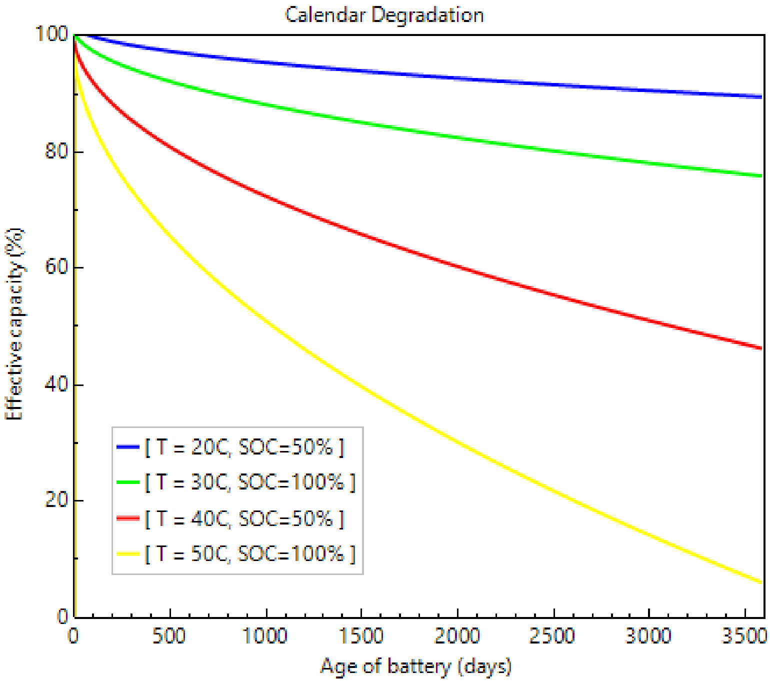


Fig.9. Battery age versus effective capacity.

Battery cycle ageing depends on the temperature, which requires careful consideration when selecting or designing of any system. Fig.9. illustrates the estimated performance degradation over the year at a low temperature of 20 °C and SoC of 50%. The effective capacity decreases to approximately 85% at the end of the year. Also, at a temperature of 30 °C and SoC of 100%, the result’s effective capacity decreased to approximately 80%. In contrast, with a high temperature of 50 °C and SoC of 100%, effective capacity at the end of the year declined to about 10%. It is clearly shown that the overall battery effective capacity ratios are deceased when the percentages of SoC and associated temperature increase.

The operating temperature can have a major impact on battery performance. The majority of batteries have an operating temperature variation where they perform at their peak performance. Hence, low or high temperatures can impair battery cycle life, capacity, and performance. Batteries that can operate in various temperatures are more adaptable and dependable.

The difference between a battery that has been fully charged and one currently in operation is known as the state of charge (SoC). The typical acceptable range of SoC is around 20% to 80%. It is related to how much electricity remains there in the cell. Equation (13) is expressed as the ratio of the remaining charge in the battery and divided via the maximum charge that the battery can deliver [38].

$$SoC(\%) = \frac{(Q_0 - Q)}{Q_{max}} x100 \qquad (13)$$

where (Q_0) represents the initial battery charge, (Q) is the quantity of electricity the battery delivers, and (Q_{max}) is the battery's maximum charge.

The performance of batteries includes not only technical characteristics but also their effect on the environment. The development of battery technology that is sustainable and environmentally friendly aims to minimise the use of harmful chemicals, lower carbon emissions during production, and boost appropriate recycling and disposal procedures.

The recently popular and modern battery for energy storage is lithium-ion because of its high energy density, long life cycle, and few maintenance needs. This high-efficiency lithium-ion (Li-ion) battery is a prototype rechargeable that usages a reversible reduction of the Li-ion in order to allow energy storage.

3.2.1. Battery Thermal Behaviour

The battery thermal behaviour is the key factor to study for performance evaluation. Understanding the various heat characteristics of batteries is important for ensuring their reliable and effective operation. The batteries produce heat when charging and discharging as a consequence of internal resistance and cell losses. The heat generation is often higher when the battery functions under substantial loads or at excessive charge and discharge rates. Effective heat dissipation is essential for maintaining battery efficiency alongside avoiding overheating. Therefore, in order to reduce the risk of runaway thermal batteries, appropriate systems for thermal management are employed in battery designs, such as thermal insulation and cooling systems.

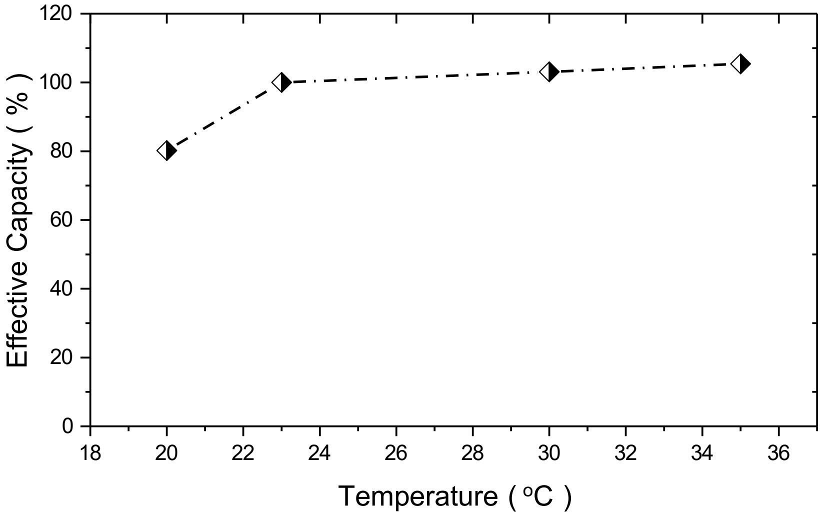


Fig. 10. Indued temperature versus effective capacity of the battery.

The battery capacity is often better at higher temperatures than at lower temperatures. As shown in Fig.10, the batteries outperformed at high temperatures; hence, as battery temperature decreased, the consequence efficiency decreased. Therefore, that will result in a decrease in the lifespan of the battery. In contrast, lower temperatures will boost the lifespan of batteries, and low temperatures will decrease battery capacity.

Previously, in the maintenance routine of traditional batteries, if any customer installed a system with an "old-fashioned battery", the system required regular checks of the liquid battery level "battery solution" of the Lead-Acid Battery (LAB) unsealed type. The energy storage devices used in conjunction with a photovoltaic solar energy system is a lead-acid battery.

The heat induces in the battery because of some phenomena due to electrochemical reactions during typical charging/discharging cycles [39, 40]. Additionally, battery heat build-up must be carefully monitored; therefore, the battery's overcharging and consequent overvoltage could cause overheating. However, to be more specific, varying ambient conditions have an impact on cycle life along with various battery parameters.

3.2.2. Battery Electrical Behaviour

Battery electrical behaviour describes how it stores and delivers electrical energy. The batteries deliver electrical energy by generating a voltage potential difference between their positive and negative terminals. It depends on their chemistry, and batteries have varying discharge behaviours. A battery's construction, chemistry and state of charge significantly determine its voltage. The battery's energy storage capacity can be determined via multiplying its capacity with the nominal battery voltage.

Temperature is an essential factor that significantly influences battery performance behaviour. Increasing temperatures can accelerate chemical processes inside the battery, accelerating capacity loss and rapid deterioration, but low temperatures can raise internal resistance and lower a battery's capacity to produce electricity.

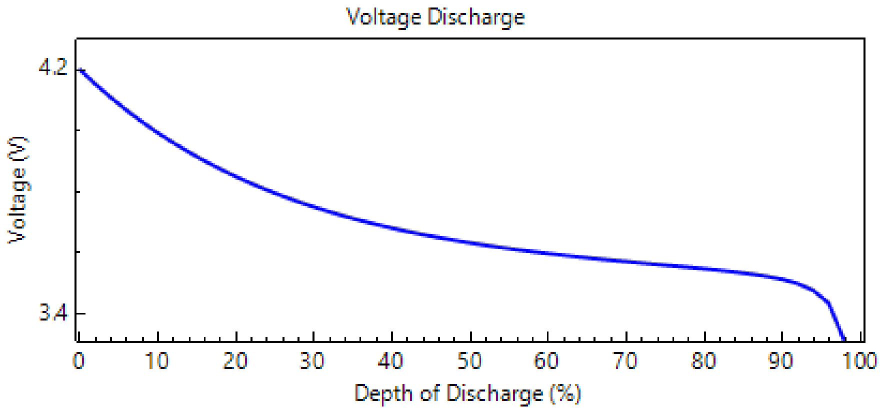


Fig.11. Performance of the battery for voltage discharge.

The internal battery configuration uses the provided nominal cell voltage. Although the battery cell's internal series resistance is about 0.001155ohm, nominal cell voltages are 3,6VDc, and the desired bank voltage is 500VDc. It is worth mentioning that the voltage of a battery is considered an important characteristic of its function.

The battery's maximum discharge current is determined by its internal series resistance. The internal resistance in batteries reduces their effectiveness in delivering electrical energy. The voltage decreases within the battery are due to the internal series resistance, particularly when large currents are being used. The lower efficiency, power loss and voltage output decrease can all be attributed to high internal resistance. When developing battery-powered systems, it's essential to take into account the internal resistance to reduce energy losses and enhance performance.

As shown in Fig.11, the performance behaviour curve of the battery for voltage discharge at a depth of discharge. As the percentage of DoD increases, the voltage will decrease under voltage discharge conditions. The voltage discharge patterns are not necessarily systematic owing to more reactions that might happen.

The method in which the battery voltage varies during discharge conditions as a result of equilibrium concentration influences, and owing to polarisation is a main characteristic of battery technology [21]. However, with such a long cycle life, the extra cycles you acquire will only be helpful for smaller DoD.

The batteries conserve energy released when there is a need for electricity, such as at nighttime or when there is not enough sunlight. The electrical load is powered by the electricity from the batteries, which ensures a constant supply of electricity even when the solar photovoltaic modules are not producing any.

Integrating a solar PV system with battery storage enables greater energy independence. Through their incorporation, additional electrical power produced by photovoltaic devices throughout the day can be utilised at night time or during periods of dim illumination. The end users can utilise it to store extra electricity to utilise afterwards, which reduces their reliance on the grid and offers backup power in case of grid failures.

It’s crucial to remember that various battery chemistries dominate in various performance characteristics. In this regard, lithium-ion batteries are appropriate for portable devices and electric vehicles due to their high energy density and long-life cycle. Other than these, flow batteries are widely used for grid-scale energy storage due to their scalability and high life cycle.

3.3. Inverter/Controller

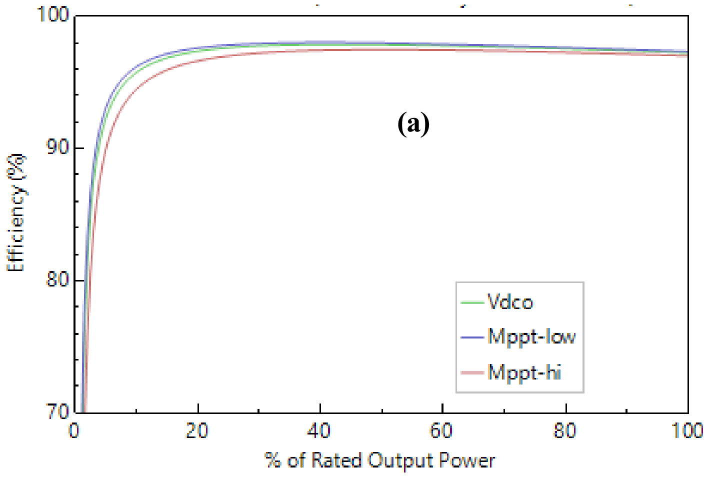
The inverter manages the energy flow among battery storage, solar photovoltaic system and electrical load. The inverter is a device which converts DC electricity produced by the solar modules into alternating current electricity. The inverter carries out this conversion procedure, which guarantees that the power can be consumed with electrical appliances.

It also relies on the inverter, which normally accompanies and controls the system’s operational voltage. As lighting, temperature, and load demands shift, the system’s output in terms of voltage and current also varies. The specification of the system inverter used “SMA America SC750CP-US (with ABB Eco Dry Ultra transformer)”. It incorporated the maximum power point tracking (MPPT) system controller.

The battery has a limit on the quantity of current that can be utilised when charging or discharging them, and using too much current may result in undesired thermal losses and reduced efficiency. In this regard, it is important to set up the discharge for the battery bank into the controller [38]. The daily functions of the inverter/controller can be expressed by the following relationship (14).

$$INV_{contral(t)} = \begin{cases} PVP_{out} \geq P_{desired}, & PV\ system\ will\ be\ energy\ source \\ PVP_{out} < P_{desired}, & the\ battery\ bank\ will\ be\ energy\ source \end{cases} \tag{14}$$

The amount of sunlight radiation received in a certain place determines the solar PV system's capacity to generate energy. The key elements of a photovoltaic (PV) system are the maximum power point tracking (MPPT) system controller, DC-AC inverter, battery storage, and photovoltaic solar module [41, 42]. However, understanding these behaviours makes identifying the most efficient battery technology for a given application easier. Moreover, it enhances energy management systems and ensures that batteries are employed safely and effectively in diverse systems and devices.



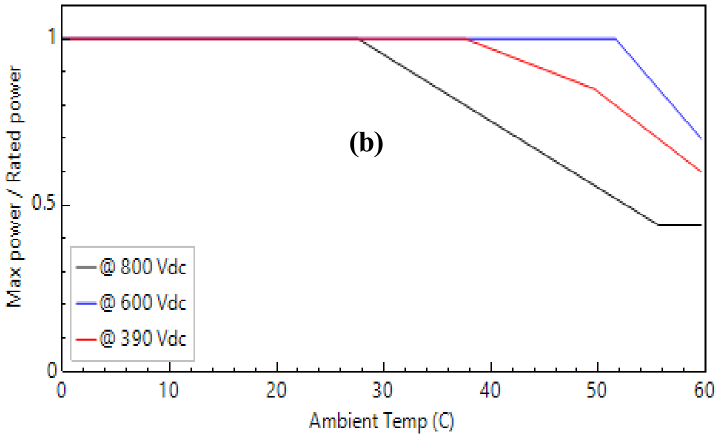


Fig. 12. Performance behaviour of the inverter (a) inverter efficiency versus rated output power (b) inverter temperature affects power.

Fig.12 illustrates the inverter efficiency versus rated power (a) and how inverter temperature affects power (b). Hence, in section (a), the rated output versus the efficiency starts from 0% and grows until a steady state at 20% of the rated output power. The efficiency will be 96%; this will be stable for voltage DC, high MPPT and low MPPT.

The ambient temperature also has an effect on inverter performance. As elucidated in Fig.11 (b), the rated power is stable at low temperatures, for @800, @600 and @390VDc. At a temperature of 30 ºC, there is a gradual decrease in the rated power at 800VDc. Also, at 40 ºC temperature, the rated power turns to decrease at 390VDc.While at 50 ºC the rated power starts to decrease at 600VDc.

4. Integration of Energy System

Energy storage systems are integrated with solar photovoltaic (PV) systems via converting the generated energy into electrochemical energy and storing it in the battery [43, 44]. The solar photovoltaic and battery storage system operates under the control of an energy management system. Thus, energy management responds to energy demand, the battery charging and discharging according to solar generation, and grid conditions, if any. This guarantees effective solar energy usage and increases the benefits of the battery storage system.

An energy management system is also utilised to monitor and control the electricity flow between the array of solar modules, battery storage, and the demand load. It optimises the battery at charging and discharging conditions based on energy availability and need.

Preserving supply and demand equilibrium and supply of power quality correction in the event of abrupt variations in voltage necessitate energy storage systems. Numerous design parameters, such as battery type, size, depth of discharge, heat, backup time, and required reserve energy, influence the energy storage system rating [45]. It is crucial to energy storage systems (ESS) as they manage how batteries are charged and discharged and other mediums of energy storage. It ensures that enough energy is available when needed, optimises the flow of energy, and monitors the condition of the batteries.

Increasing system efficiency can be achieved by adding batteries to a photovoltaic system; this may boost the system’s overall effectiveness. The excess electricity produced by solar modules during periods of low energy demand can be stored in the batteries, in contrast to being lost during such times. This enhances the comprehensive utilisation of the solar energy generated.

It is important to mention that a solar photovoltaic system coupled with a battery can help industrial and commercial customers lower peak demand fees. Therefore, the industries sector can reduce their electricity costs by releasing stored energy at times of high demand.

Systems with solar and storage can potentially offer services to the grid. Therefore, battery energy could be released to keep up the grid during periods of high electrical demand, relieving pressure on utility buildings. Some solar photovoltaic systems incorporating a battery can be monitored and controlled remotely. Through a "user-friendly interface", these systems enable users to monitor the efficiency of their solar devices, the status of the batteries, and the consumption of energy. Some systems may even allow for remote control of energy flows and configurations for the best system performance.

As development and research efforts focus on enhancing current battery technologies and inventing novel types, battery performance continues to improve. Further applications, a rise in the use of clean/renewable energy sources, and the overall development of energy storage systems are influenced by improved performance.

The future scalability of a PV system with batteries should be taken into account during installation; since the demands for energy increase or technology develops, it might have the choice to install additional photovoltaic arrays or increase the battery storage capacity. It is essential to consider future scalability when designing the initial system in order to fulfil all potential requirements. Further energy system integration is to consider the technology of smart energy technology devices and autonomous control. Besides, referring to the revolution of information technology can use artificial intelligence technology in future design.

5. Conclusions

This study analysed a solar photovoltaic system integrated with a battery, also known as a solar-plus-storage system, incorporating solar modules with energy storage characteristics. This combination allows extra electricity produced by the solar module array during the day to be stored and used at night or during periods of insufficient sunlight.

Based on the results and discussion analysis, it elucidates integrating a solar photovoltaic system is gaining a greater performance and higher availability. Energy efficiency can be increased by using a photovoltaic system with integrated battery storage, i.e., the energy management system acts to optimise/control the system's performance. In addition, the energy management system incorporates solar photovoltaic battery energy storage can enhance the system design under various operating conditions.

From the battery's electrical performance behaviour, the battery's number of cycles depends on the depth of discharge. Thus, the battery cycle lifetime and capacity increase with the increase of DoD. The overall battery effective capacity ratios are deceased when the percentages of SoC and associated temperature increase.

The thermal performance characteristics of the integrated model devices are considered. Based on that temperature sensitivity was investigated, and it was deduced that inverters at high temperatures have affected the performance parameters. Moreover, an increase in temperature also affects solar PV modules, which decreases their performance. Unlike this, the batteries perform well at high temperatures; hence, their best capacity is at high temperatures, but in conventional batteries, the corresponding battery's lifespan decays at an increased rate. The appropriate thermal management can manipulate the trade-off between high and low temperatures and associated costs.

From the model, it is deduced that the system has an annual estimated energy yield of approximately 1,353 kWh/kW and a performance ratio of 0,85. The highest energy yield occurred during the summer (May-August), owing to more sunshine hours and high solar intensity values.

Further upcoming works will include an investigation by experimental/numerical analysis of building integrated photovoltaic (BIPV), particularly during peak load demand periods, where there is a demand for more energy to power the air conditioning systems, etc. Furthermore, the study of solar PV-battery levelised the cost of electricity needs to be estimated in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Many grateful thanks to the Libyan Authority for Research Science and Technology, and many thanks to the staff in the Libyan Centre for Research and Development of Sahrain Communities. Also, many thanks to the anonymous reviewers for their constructive comments in improving this paper.

References

[1] H. Wang, B. Ang, B. Su. A multi-region structural decomposition analysis of global CO2 emission intensity. Ecological Economics. 142 (2017) 163-76. https://doi.org/10.1016/j.ecolecon.2017.06.023.

[2] D. Gielen, F. Boshell, D. Saygin, M.D. Bazilian, N. Wagner, R. Gorini. The role of renewable energy in the global energy transformation. Energy Strategy Reviews. 24 (2019) 38-50. https://doi.org/10.1016/j.esr.2019.01.006.

[3] J. Bei, C. Wang. Renewable energy resources and sustainable development goals: Evidence based on green finance, clean energy and environmentally friendly investment. Resources Policy. 80 (2023), 103194. https://doi.org/10.1016/j.resourpol.2022.103194.

[4] UNFCCC. Paris Agreement-Status of Ratifcation, United Nations Framework Convention on Climate, 2016. https://unfccc.int/process/the-paris-agreement/status-of-ratifcation (25 January 2022, date last accessed). 2016.

[5] UNFCCC. The Paris Agreement. Archived from the original on 19 March 2021. Retrieved 18 September 2021. https://unfccc. int/process-and-meetings/the-paris-agreement/the-parisagreement (2 February 2022, date last accessed).]. 2021.

[6] N. Panwar, S. Kaushik, S. Kothari. Role of renewable energy sources in environmental protection: A review. Renewable sustainable energy reviews. 15 (2011) 1513-24. https://doi.org/10.1016/j.rser.2010.11.037.

[7] A. Qazi, F. Hussain, N.A. Rahim, G. Hardaker, D. Alghazzawi, K. Shaban, et al. Towards sustainable energy: a systematic review of renewable energy sources, technologies, and public opinions. IEEE access. 7 (2019) 63837-51. DOI: 10.1109/ACCESS.2019.2906402.

[8] M. Combe, A. Mahmoudi, M.H. Haque, R. Khezri. Optimal sizing of an AC-coupled hybrid power system considering incentive-based demand response. IET Generation, Transmission Distribution. 13 (2019) 3354-61. https://doi.org/10.1049/iet-gtd.2018.7055.

[9] R. Khezri, A. Mahmoudi, H. Aki. Optimal planning of solar photovoltaic and battery storage systems for grid-connected residential sector: Review, challenges and new perspectives. Renewable Sustainable Energy Reviews. 153 (2022) 111763. https://doi.org/10.1016/j.rser.2021.111763.

[10] IRENA. Solar Energy—International Renewable Energy Agency.www.irena.org/solar (2 February 2023, date last accessed). 2021.

[11] M. Hosenuzzaman, N.A. Rahim, J. Selvaraj, M. Hasanuzzaman, A.A. Malek, A. Nahar. Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation. Renewable sustainable energy review. 41 (2015) 284-97. https://doi.org/10.1016/j.rser.2014.08.046.

[12] A.O. Maka, J.M. Alabid. Solar energy technology and its roles in sustainable development. Clean Energy. 6 (2022) 476-83. https://doi.org/10.1093/ce/zkac023.

[13] K. Obaideen, A.G. Olabi, Y. Al Swailmeen, N. Shehata, M.A. Abdelkareem, A.H. Alami, et al. Solar energy: Applications, trends analysis, bibliometric analysis and research contribution to sustainable development goals (SDGs). Sustainability. 15 (2023) 1418. https://doi.org/10.3390/su15021418.

[14] G.T. Chala, S.M. Al Alshaikh. Solar Photovoltaic Energy as a Promising Enhanced Share of Clean Energy Sources in the Future—A Comprehensive Review. Energies. 16 (2023) 7919. https://doi.org/10.3390/en16247919.

[15] K. Divya, J. Østergaard. Battery energy storage technology for power systems—An overview. Electric power systems research. 79 (2009) 511-20. https://doi.org/10.1016/j.epsr.2008.09.017.

[16] A. Mayyas, A.A. Chadly, I. Khaleel, M. Maalouf. Techno-economic analysis of the Li-ion batteries and reversible fuel cells as energy-storage systems used in green and energy-efficient buildings. Clean Energy. 5 (2021) 273-87. https://doi.org/10.1093/ce/zkab009.

[17] J. Mitali, S. Dhinakaran, A. Mohamad. Energy storage systems: A review. Energy Storage Saving. (2022). https://doi.org/10.1016/j.enss.2022.07.002.

[18] M. Hasan, H. Serra Altinoluk. Current and future prospective for battery controllers of solar PV integrated battery energy storage systems. Frontiers in Energy Research. 11 (2023) 1139255. https://doi.org/10.3389/fenrg.2023.1139255.

[19] A. Joseph, M. Shahidehpour. Battery storage systems in electric power systems. 2006 IEEE Power Engineering Society General Meeting. IEEE2006. p. 8 pp. DOI: 10.1109/PES.2006.1709235.

[20] B. Li, Z. Liu, Y. Wu, P. Wang, R. Liu, L. Zhang. Review on photovoltaic with battery energy storage system for power supply to buildings: Challenges and opportunities. Journal of Energy Storage. 61 (2023) 106763. https://doi.org/10.1016/j.est.2023.106763.

[21] C. Honsberg, S. Bowden. PV education. ORG. http://pveducation. org/pvcdrom/properties-of-sunlight/sun-position-calculator. (2014).

[22] Y. Li, J. Wu. Optimum integration of solar energy with battery energy storage systems. IEEE Transactions on Engineering Management. 69 (2020) 697-707. DOI: 10.1109/TEM.2020.2971246.

[23] A. Chadly, E. Azar, A. Mayyas. Uncertainty and simulation-based cost analyses for energystorage systems used in green buildings. International Journal of Energy Research. 46 (2022) 14346-70. https://doi.org/10.1002/er.8150.

[24] R. Elazab, O. Saif, A.M. Amin Metwally, M. Daowd. New smart home energy management systems based on inclining block-rate pricing scheme. Clean Energy. 6 (2022) 503-11. https://doi.org/10.1093/ce/zkac016.

[25] V. Mudgal, P. Singh, S. Khanna, C. Pandey, V. Becerra, T.K. Mallick, et al. Optimization of a novel Hybrid Wind Bio Battery Solar Photovoltaic System Integrated with Phase Change Material. Energies. 14 (2021) 6373. https://doi.org/10.3390/en14196373.

[26] T. Iqbal, Y.H.M. Dabas. Sizing and Analysis of a DC Stand-Alone Photovoltaic-Battery System for a House in Libya. Jordan Journal of Electrical Engineering. 7 (2021) 84-95. https://doi.org/10.5455/jjee.204-1612977821.

[27] B.T. Mirletz, D.L. Guittet. Heuristic dispatch based on price signals for behind-the-meter pv-battery systems in the system advisor model. 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). IEEE2021. pp. 1393-400. DOI: 10.1109/PVSC43889.2021.9519013.

[28] Z. Wang, Y. Xiao, Y. Wan, K. Liu, X. Wang. Research on energy management strategy of photovoltaic–battery energy storage system. International Journal of Low-Carbon Technologies. 17 (2022) 488-93. https://doi.org/10.1093/ijlct/ctac024.

[29] D. Borkowski, P. Oramus, M. Brzezinka. Battery energy storage system for grid-connected photovoltaic farm–Energy management strategy and sizing optimization algorithm. Journal of Energy Storage. 72 (2023) 108201. https://doi.org/10.1016/j.est.2023.108201.

[30] R. Behmann, J. Phan, A. Root, M. Schmidt, W.G. Bessler. Integration of a lithium-ion battery in a micro-photovoltaic system: Passive versus active coupling architectures. Solar Energy. 262 (2023) 111748. https://doi.org/10.1016/j.solener.2023.05.025.

[31] M. Hammami, S. Torretti, F. Grimaccia, G. Grandi. Thermal and performance analysis of a photovoltaic module with an integrated energy storage system. Applied Sciences. 7 (2017) 1107. https://doi.org/10.3390/app7111107.

[32] O. Nkuriyingoma, E. Özdemir, S. Sezen. Techno-economic analysis of a PV system with a battery energy storage system for small households: A case study in Rwanda. Frontiers in Energy Research. 10 (2022) 957564. https://doi.org/10.3389/fenrg.2022.957564.

[33] R.G. Allwyn, A. Al-Hinai, R. Al-Abri, A. Malik. Optimization and techno-economic analysis of PV/Battery system for street lighting using genetic algorithm–a case study in Oman. Cleaner Engineering Technology. 8 (2022) 100475. https://doi.org/10.1016/j.clet.2022.100475.

[34] A.O. Maka, T.S. O'Donovan. Effect of thermal load on performance parameters of solar concentrating photovoltaic: High-efficiency solar cells. Energy Built Environment, 3(2022) 201-9. https://doi.org/10.1016/j.enbenv.2021.01.004.

[35] T.N. Chaudhary, A.O. Maka, M.W. Saleem, N. Ahmed, M.U. Rehman, M.U. Azeem. Experimental and Performance Evaluation of the Soiling and Cooling Effect on the Solar Photovoltaic Modules. Arabian Journal for Science Engineering, (2023) 1-12. https://doi.org/10.1007/s13369-023-07858-x.

[36] A.O. Maka, T.S. O'Donovan. Dynamic performance analysis of solar concentrating photovoltaic receiver by coupling of weather data with the thermal-electrical model. Thermal Science Engineering Progress. 24 (2021) 100923. https://doi.org/10.1016/j.tsep.2021.100923.

[37] D.R. Myers. Solar radiation modeling and measurements for renewable energy applications: data and model quality. Energy. 30 (2005) 1517-31. https://doi.org/10.1016/j.energy.2004.04.034.

[38] N. DiOrio, A. Dobos, S. Janzou, A. Nelson, B. Lundstrom. Technoeconomic modeling of battery energy storage in SAM. National Renewable Energy Lab.(NREL), Golden, CO (United States)2015. https://doi.org/10.2172/1225314.

[39] P. Jindal, R. Katiyar, J. Bhattacharya. Evaluation of accuracy for Bernardi equation in estimating heat generation rate for continuous and pulse-discharge protocols in LFP and NMC based Li-ion batteries. Applied Thermal Engineering. 201 (2022) 117794. https://doi.org/10.1016/j.applthermaleng.2021.11779.

[40] G.A. Farulla, V. Palomba, D. Alosio, G. Brunaccini, M. Ferraro, A. Frazzica, et al. Optimal design of lithium ion battery thermal management systems based on phase change material at high current and high environmental temperature. Thermal Science Engineering Progress. 42 (2023) 101862. https://doi.org/10.1016/j.tsep.2023.101862.

[41] M. Irfan, Z.-y. Zhao, M. Ahmad, A. Rehman. A techno-economic analysis of off-grid solar PV system: A case study for Punjab Province in Pakistan. Processes. 7 (2019) 708. https://doi.org/10.3390/pr7100708.

[42] A.A. Elbaset, S.A.M. Abdelwahab, H.A. Ibrahim, M.A.E. Eid. Performance analysis of photovoltaic systems with energy storage systems. Springer2019.

[43] H. Akbari, M.C. Browne, A. Ortega, M.J. Huang, N.J. Hewitt, B. Norton, et al. Efficient energy storage technologies for photovoltaic systems. Solar Energy. 192 (2019) 144-68. https://doi.org/10.1016/j.solener.2018.03.052.

[44] J.D.A. Mariano, J. Urbanetz Jr. The Energy Storage System Integration Into Photovoltaic Systems: A Case Study of Energy Management at UTFPR. Frontiers in Energy Research. 10 (2022) 831245. https://doi.org/10.3389/fenrg.2022.831245.

[45] K. Prakash, M. Ali, M.N.I. Siddique, A.A. Chand, N.M. Kumar, D. Dong, et al. A review of battery energy storage systems for ancillary services in distribution grids: Current status, challenges and future directions. Frontiers in Energy Research. 10 (2022) 971704. https://doi.org/10.3389/fenrg.2022.971704.