Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Off-Grid Solar PV System Design in Isolated Island for Sustainable Energy Access: A Case Study in Sukun Island, Indonesia

Handrata Roy Josia[a,*]

[a]*Department of Electrical Power Engineering, School of Electrical Engineering and Informatics, Bandung Institute of Technology, Bandung, Indonesia*

ARTICLE INFO

Article Type:

Research Article

Received:06.06.2023
Accepted:07.10.2023

Keywords:
Solar Power Plant
Battery Energy Storage System (BESS)
Quasi-dynamic Analysis
System Stability
PVsyst
DIgSILENT Powerfactory

ABSTRACT

This paper presents a preliminary study on the design of an off-grid solar PV system for an isolated island. It conducts a case study for Sukun Island that has the highest potential for solar energy in Indonesia. The study includes climate research, consumption estimation, system sizing, simulation, quasi-dynamic analysis, and environmental analysis. Climate data from Solargis and Meteonorm is utilized. The greatest difficulty in conducting an initial PV system planning study is pre-sizing. Using PVsyst simulation, this study confirms the validity of simplified theoretical calculations stated in the paper for system pre-sizing, with the theoretically calculated system (285 kWp solar power plant with 2.91 MWh storage system) managed to get a Loss of Load Probability (LOLP) valued at 0.17%, meeting applicable standard. The proposed method of combining simulation using PVsyst and quasi-dynamic analysis using DIgSILENT Powerfactory can be used to verify the power stability of the designed PV-BESS system. The simulations attest to the use of battery energy storage systems (BESS) in maintaining the stability of the solar PV network by preventing the vulnerability of electrical networks to insufficient electricity (loss of load) and voltage sags, proven by the minimum voltage level of 96.6%, meeting international safety standards.

1. Introduction

Electricity is one of the most important aspects of modern life. It is necessary for all parts of society to have electricity that is reliable and economical. Mucahit [1] investigated whether there is a long-term relationship between electricity consumption and economic growth. Even so, in developing countries, there are several problems to be faced in implementing electricity, especially in rural areas.

*Corresponding Author Email:marbunhandrata@gmail.com

Cite this article: Josia, H. (2023). Off-Grid Solar PV System Design and Analysis in Isolated Island for Sustainable Energy Access: A Case Study in Sukun Island, Indonesia. Journal of Solar Energy Research, 8(3), 1609-1621. doi: 10.22059/jser.2023.360373.1318

DOI: 10.22059/jser.2023.360373.1318 DOR: 20.1001.1.25883097.2023.8.3.4.4

Blimpo and Cosgrove-Davies [2] stated that these include policy stability, technical support, and technology flexibility. Furthermore, COP23 [3] declared that isolated islands are considered the most vulnerable areas to climate change and rising sea levels in the world.

Jaiswal et al [4] concluded that the advancement and refinement of sustainable energy sources have the potential to significantly contribute to both economic expansion and the preservation of environmental well-being. However, Alshardy et al [5] found that, like most developing countries in the world, several areas in Indonesia do not have access to electricity. One example is the province of East Nusa Tenggara (NTT). It is a province that has the lowest electrification rate, as low as 92.33%, as discovered by Likadja et al [6]. The main reason behind this is the geographical aspect of the province, which has hundreds of isolated islands that can’t be connected to on-grid electricity on bigger islands like Timor Island.

Mustayen et al [7] stated that off-grid systems have traditionally relied heavily on diesel engines or fossil fuels, with the problem being pollution and high fuel costs. Nuttall et al [8] found that pursuing low-carbon targets while reducing reliance on non-renewable sources has created powerful economic incentives to execute the transition to renewable energy. Kalbasi et al [9] observed that using renewable energy sources gets rid of unknown future fuel costs, but at the risk of high upfront investments. Solar power plants are considered the better option for off-grid power plants on remote islands for several reasons.

1. Plenty of Sunlight: Amiroh et al [10] concluded that remote islands, especially those near the equator, receive plenty of direct sunlight all year round. Solar power plants take advantage of this abundant sunlight and convert it into electricity.
2. Energy independence: Remote islands often rely on imported fossil fuels to meet their energy needs, which can be expensive and logistically challenging, as discussed by Alves et al [11]. Sanchez et al [12] advised using solar power plants to provide a renewable local source of energy, reducing dependence on fossil fuels.
3. Environmental compatibility: Solar energy is a clean and renewable energy source. Kabeyi and Olanrewaju [13] stated that there was near-zero carbon emission during its operation, contributing to the mitigation of climate change and reducing the impact on the environment.
4. Scalability and Modularity: Solar power plants can be designed to meet the unique energy needs of remote islands. Hannan et al [14] confirmed that solar power plants can be easily scaled up or down, allowing incremental expansion as the island's population and energy demand increase.
5. Long term cost savings: The initial investment to install a solar power plant can be higher than a conventional power plant, but Steffen et al [15] found that in the long run, the operating costs of solar energy are lower. Running costs are relatively low and are mainly limited to maintenance and occasional part replacements.
6. Resilience and Reliability: Ghadimi et al [16] stated that solar power plants can be equipped with energy storage systems, such as batteries, to store excess energy during the day and use it at night or when solar irradiation is low. This makes the power supply more reliable, reducing the risk of blackouts and outages on remote islands and also avoiding overvoltage issues, as observed by Al-Saffar and Musilek [17].

A solar power plant utilizes photovoltaic technology in solar cells that convert solar irradiation into electric current. Kumar et al [18] stated that it also needs some main auxiliaries, such as batteries and inverters. Lakshika et al [19] confirmed that a solar inverter is required to convert DC (direct current) to AC (alternating current) that can be used on existing electrical loads.

Naderipour et al [20] stated that one of the main problems of solar-based power plants is load loss, a situation where available generated power is less than the system load. Yin et al [21] described that Loss of Load Probability (LOLP) in a solar power plant as a metric used to assess the reliability and adequacy of power supply from a renewable energy source, such as solar power, to meet demand. It quantifies the likelihood or probability that the power plant's output will not be sufficient to meet the load or demand during a specific time period, usually expressed in percentage or hours per year.

Khalkho et al [22] investigated that LOLP takes into account various factors, including the intermittent nature of solar energy due to weather conditions (cloud cover, nighttime, etc.), system design, operational constraints, and the balance between power generation and load requirements. It's an important metric for ensuring a consistent and reliable power supply, especially in off-grid or hybrid systems where there isn’t any grid backup.

By assessing how often and for how long the system's generation falls short of meeting the demand, the probability of load shedding or outages due to inadequate power supply can be determined. Sulaiman et al [23] stated that their metric helps system designers, operators, and planners make informed decisions about system sizing, backup solutions, and energy storage requirements to ensure a desired level of reliability.

This paper will discuss the design of a solar PV system to meet electricity needs on Sukun Island, one of the most isolated islands in East Nusa Tenggara (NTT), as an example of an isolated island. The solar PV system is expected to help improve the quality of life in the area. Proper and well-directed management of electrical energy resources will help the area develop optimally.

The power generation and required size of a PV system can be estimated using the simulation software PVSyst. PVSyst software will be used to design and simulate a photovoltaic system to meet the energy demands of Sukun Island. What sets this paper apart from its predecessors is the combination of PVsyst with DigSILENT PowerFactory for simulation and analysis. Several of the newest papers by Kumar et al [24], Satish et al [25], and Salmi et al [26] only paid attention to the performance (yield ratio) of a solar power system without regard to the voltage level or LOLP of the system.

Thotakura et al [27] stated that the photovoltaic (PV) yield ratio is a metric that evaluates the efficiency and performance of a solar photovoltaic system by comparing the actual energy output to the theoretically calculated energy output. The PV yield ratio primarily focuses on the energy generated by the solar panels during daylight hours and compares it to the energy that could be generated under ideal conditions. While the PV yield ratio provides valuable insights into the efficiency of the solar PV system, Zhao et al [28] observed that it doesn't directly address the aspect of system reliability in terms of meeting the required voltage, or LOLP.

The analysis of LOLP will be carried out on PVsyst, while the analysis of system voltage will be carried out on quasi-dynamic analysis using DigSILENT Powerfactory. Starčević et al [29] confirmed that quasi-dynamic analysis in the context of electric systems refers to a method of analysis that falls between static and dynamic analyses. Zare Oskouei and Mohammadi-Ivatloo [30] described that it examines the steady-state conditions as well as the time-varying behavior of the system.

This paper will assess the hourly voltage level of the system, which involves considering the energy generation profile, load demand profile, and storage capacity. This is the time when DigSILENT PowerFactory performs quasi-dynamic analysis so that the designed PV-BESS system can provide constantly available electricity with a voltage that complies with applicable standards.

2. Materials and Methods

The methodology used in this study began with a preliminary survey of similar papers in the electric energy field. After a preliminary survey, the location of the planned solar PV system was determined. The climatic conditions and weather in the area were investigated. The data comes from meteorological databases, papers, and international online databases.

Once the location and power consumption were determined, simulations for the construction of the solar power plant were conducted. After determining the required energy consumption and suitable installation locations, this study used PVSyst software to analyze system performance technically. Digsilent Powerfactory is then used to simulate the quasidynamic load flow of the observed system. The research-related flowchart is shown in Figure 1.

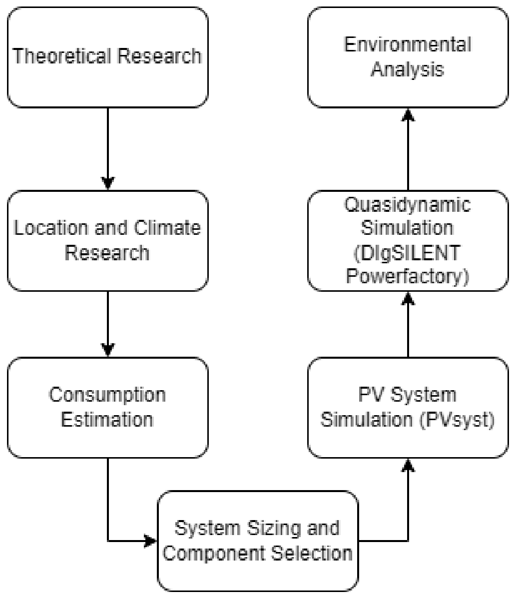

Figure 1. Flowchart Methodology of the Study

2.1. Study Location

In this study, Sukun Island, West Alok, Sikka, and East Nusa Tenggara are selected as the sites. This research was conducted in an effort to address the importance of electricity in an area that doesn't have any connection to the electrical grid. It is also an area consisting of low- and middle-income communities. The research site is more precisely located at the following coordinates: -8.1137, 122.1183.

As many as 1,088 residents of Sukun Island, Semparong Village, Alok District, and Sikka Regency are eager for electricity and telecommunication networks. Difficulties in accessing these aspects make it difficult for the public to report incidents and obtain information. The closest city to this island is Maumere, with a travel time of 3 hours via sea transportation.

Figure 2. Specific Location of Installation on Google Earth

Establishing an on-grid electricity connection in an area that is located far from the national grid can present several challenges and complications. This includes infrastructure costs as observed by Hassan [31], power losses as observed by Hayes et al [32], and maintenance difficulties as observed by Luo et al [33]. These challenges result in the need to use off-grid electricity. With an area of 4.882 km^2, this island is considered big enough for the construction of the solar PV system to provide their own electricity without relying on the national grid.

2.2. Location Climate Parameters

East Nusa Tenggara also has a very good potential for solar energy. This province has the best solar energy potential in Indonesia, mainly thanks to its high global horizontal irradiation. This potential is based on data from Solargis that is conferred as follows: Based on Figure 3, this site has a relatively higher direct normal irradiation than the average of other Indonesian areas.

The data in Figure 4 represent the average hourly profiles of direct normal irradiation in the area. It is shown that most of the time, energy can be obtained from 6:00 a.m. to 6:00 p.m. Most of the daytime load can be supplied without using batteries, while the

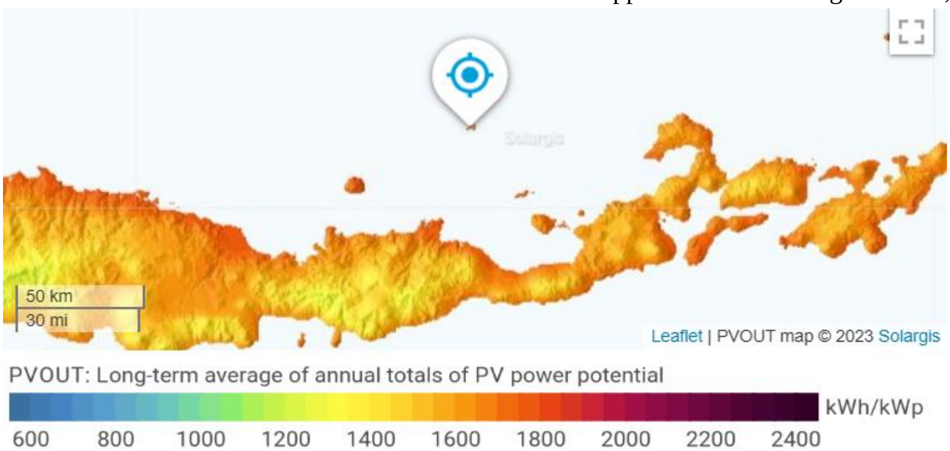

Figure 3. Direct Normal Irradiation in the Location of Installation on Solargis

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6										28	34	15
6 - 7	112	124	168	165	200	142	134	154	242	305	266	172
7 - 8	240	289	366	445	432	437	441	465	480	473	388	261
8 - 9	331	383	462	554	541	550	568	604	622	609	501	337
9 - 10	395	436	535	640	623	640	652	692	716	693	589	405
10 - 11	441	501	579	692	673	690	706	766	777	759	654	448
11 - 12	464	530	619	714	693	715	742	795	799	765	673	488
12 - 13	464	554	646	702	694	708	734	800	774	651	537	452
13 - 14	431	457	633	686	668	683	709	780	734	599	487	412
14 - 15	418	472	582	637	608	625	662	723	695	652	585	391
15 - 16	328	392	478	522	504	530	568	627	595	538	475	302
16 - 17	232	270	346	393	362	391	435	469	428	368	324	215
17 - 18	115	134	147	85	56	61	81	154	78	53	62	88
18 - 19												
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	3972	4542	5562	6235	6052	6171	6432	7030	6941	6494	5574	3986

Figure 4. Average Hourly Profiles of Direct Normal Irradiation on Solargis

nighttime load can be supplied with the battery that is being charged during daylight.

2.3. Simulation Climate Parameters

In PVsyst, a meteo file is a data file that contains meteorological data, such as solar irradiance, temperature, and wind speed, which is used as input for the simulation and analysis of photovoltaic (PV) systems. Kumar et al [24] stated that Meteo files are used to represent the climate conditions of a specific location or region and are crucial for accurate performance prediction and energy yield assessment of PV systems. The meteorological database for simulation can be taken from AEMET, NASA, Meteonorm, ISPRA-GIS, Helios, Solaris, etc. PVsyst uses it to simulate and analyze the performance of PV systems under different weather conditions, including solar energy production, and temperature effects on PV module performance. In this study, meteo data from Meteonorm 8.0 (2010-2014), Sat=100% is being used. The data is stated in table 1.

Sari et al [34] assessed that sunpath diagram, also known as a solar path diagram or solar chart, is a graphical representation that illustrates the path that the sun takes across the sky at different times of the year for a specific location on Earth. It provides valuable information about how the sun's position changes over time, which is crucial for understanding solar energy availability, shading analysis, and architectural design. As seen in Figure 5, the solar elevation angle changes throughout the day as the sun rises, reaches its highest point (solar noon), and sets. The solar elevation will be 0° from 6 p.m. until 6 a.m. the next day, meaning that electrical energy can be harnessed from 6 a.m. until 6 p.m.

Table 1. Monthly Meteo Data of The Location

Month	*GHI* $kWh/m^2/day$	*HDI* $kWh/m^2/day$	*Temperature* ℃
January	5.59	2.81	27.5
February	5.00	2.79	27.3
March	5.42	2.54	27.4
April	6.12	2.14	27.3
May	5.47	1.88	27.4
June	5.35	1.66	26.0
July	5.62	1.65	26.0
August	6.10	1.98	26.1
September	6.24	2.28	26.9
October	6.55	2.62	28.5
November	6.43	2.48	28.5
December	6.03	2.75	28.0

Table 1 shows the GHI, HDI, and temperature of the location that will be the main aspect for PVsyst in predicting the electricity production of the PV system monthly.

2.4. Electricity Consumption Estimation

Before the PVSyst simulation is done, calculations are used to estimate load requirements in the area. By estimating the load requirements, solar PV system design can be approximated. This approximation will be simulated to ensure the reliability of the PV system design that has been carried out. Sizing is done to determine the optimum combination of array size and storage capacity based on load requirements in the village. The specifications of the load required are as follows.

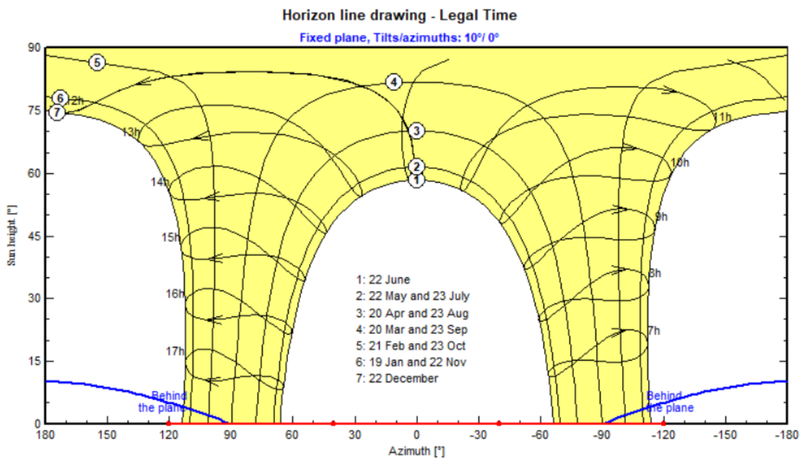

Figure 5. Sunpath Diagram of the Location

Table 2. Load Requirements in Sukun Island

Equipment	*Units*	*Power (Watts)*	*Daily Usage (Hours)*
Peak Residential Load	320	30	2
Intermediate Residential Load	320	80	6.5
Base Residential Load	320	90	24
Lighting System	100	20	12
Water Pump	10	500	4
Commercial Load	15	400	7

2.5. Electricity System Estimation

The PV module serves as the primary component of the solar PV system, responsible for converting the energy from the sun's light into direct current (DC) electricity. This DC electricity is then stored in the battery using a controller. The power generated by the module, denoted as P_{PV}, can be calculated using the following formula by Khatib et al [35].

$$P_{PV} = \frac{E_{load}}{\eta_S \eta_{inv} psh} S_f \tag{1}$$

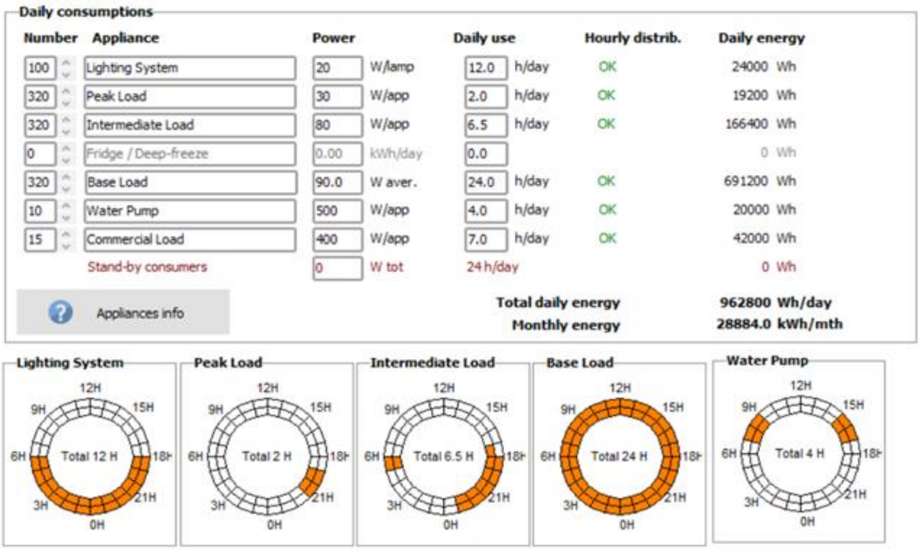

Figure 6. Daily Load Setting

The hourly distribution of the daily load requirements as stated in Figure 6 is plotted as follows: 542,400 Wh are needed for night load and 420,400 Wh are needed for day load, making a total of 962,800 Wh daily. It is assumed that the loads are constant over the year. This results in a load profile that is peaked at 19:00–21:00, as depicted in Figure 7 from PVsyst software.

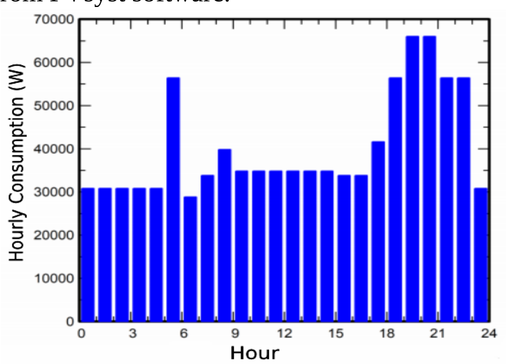

Figure 7. Load Profile of the System

where E_{load} is the total load in Wh, psh is the peak sun hour in h, η_S and η_{inv} is the efficiency of PV and inverter system in %, and S_f is the safety factor.

Another vital element of a photovoltaic system is the battery storage, which is incorporated into the system to provide electricity during the night. The size and capacity of the battery are optimized to ensure reliable performance throughout the year. The capacity of the battery, denoted as C_{bat}, can be calculated using the following equation from Ibrahim et al [36].

$$C_{bat} = \frac{E_{load} A_u}{\eta_{bat} DODV_{bat}} \tag{2}$$

where E_{load} is the total load (night) in Wh, A_u is the number of autonomy days, η_{bat} is the efficiency of batter in %, DOD is depth of discharge in %, and V_{bat} is the nominal voltage of the battery. These equations will be evaluated and verified through the simulations using PVsyst.

3. Results and Discussion

Solar PV design is a detailed process that involves careful consideration of various specifications to ensure an efficient and effective photovoltaic system. This includes evaluating site conditions, determining system sizing based on energy demand, selecting appropriate PV panels and inverters, designing electrical and mechanical components, and analyzing system performance.

Abubakar and Almeida [37] discussed that system sizing plays a vital role in determining the number and type of solar panels needed to efficiently capture solar energy, as well as calculating the battery capacity required to store and save energy for periods of low or no sunshine, This requires careful consideration of factors such as load requirements, peak demand, solar irradiation, and ground space in the location for PV installation.

As stated in the methodology, after determining the required power consumption and suitable installation location, component sizing and selection are done using the discussed formulas. After that, this study used PVSyst for technical analysis of system performance and Digsilent Powerfactory to simulate the quasi-dynamic load flow of the observed system. All of this are done to prove the formulas and evaluate the system so that it complies with applicable standards.

3.1. Component Sizing and Selection

Component sizing and selection are one of the important aspects of solar PV design, which involves choosing the right PV panels, inverters, and other system components that are compatible and efficient for the specific project. Factors such as panel efficiency, inverter type, and other parameters are considered during component selection.

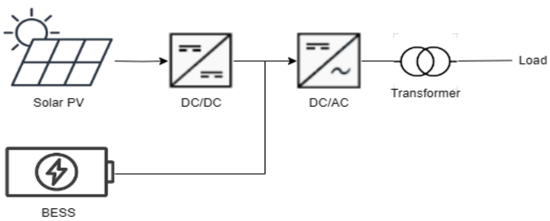

Figure 8. Basic Structure of
Solar Power Generation System

This off-grid solar power generation system comprises several solar PV modules paralleled to battery energy storage system (BESS) that are connected in series with an inverter, making it DC-coupling/BESS side solar PV system, as recommended by Lo Franco et al [38] based on its efficiency. The inverter serves as a link between the modules and the controller. The controller plays a crucial role in managing the flow of power from the solar power generation system to both the battery branch and the user.

Two equations from Part 2.3 of this paper, equation (1) and equation (2), are now applied to calculate the load requirements, which are already specified in Table 2. For a simple calculation purpose, the efficiency of the PV system is set to 0.8, the efficiency of the inverter is set to 0.9, and the safety factor is set to 1.1. The needed watt-peak of the system can be calculated as follows.

$$P_{PV} = \frac{962800}{0.8 \times 0.9 \times 4.849} \times 1.1 = 285505 Wp \quad (3)$$

As it has been shown, a solar PV system size of 303,350 Wp is needed to ensure the availability of sustainable electricity for the load. After calculating the needed solar PV system size, battery size also needs to be considered. To simplify the calculation, the depth of discharge is set to 0.6, and the efficiency of the battery is set to 0.8. Ali and Saleh [39] recommended 2-3 autonomy days so that the battery would be large enough to supply continuous energy for full 2-3 days without charging. 2.5 is taken for the calculation. To make a more reliable and resilient system during the night, with a nominal battery voltage of 874 volts (as specified in Table 4), the battery storage needed by the system can be calculated as follows.

$$C_{bat} = \frac{542000 \times 2.5}{0.8 \times 0.6 \times 874} = 3230 Ah \quad (4)$$

It is calculated that a battery storage of 3230 Ah is needed to ensure the availability of electricity at night when sunlight is not available. The solar panels and batteries that are used in the simulation are specified as follows.

Table 3. Solar Panel Parameters

Parameters	***Value***
Nominal Power	570 Wp
Short Circuit Current	13.67 A
Max Power Point Current	12.99 A
Temperature Coefficient	0.048 %/°C
Open Circuit Voc	53.09 V
Max Power Point Voltage	43.89V

Table 4. Battery Parameters

Parameters	***Value***
Nominal Voltage	873.8 V
Capacity at C10	222.3 Ah
Charge Cut-Off Voltage	999.6 V
Discharge Cut-Off Voltage	714.0 V
Voltage at SOC = 50%	880.6 V
Columbic Efficiency	96.0 %

These results are used as a consideration to calculate units needed for solar panels and batteries specified in Table 3 and Table 4. Considering the size of overall PV and battery system needed and the size of PV and battery system per unit, the calculations are as follows.

$$n_{PV} = \frac{285505}{570} = 500 units \tag{5}$$

$$n_{bat} = \frac{3230}{222.3} = 15 units \tag{6}$$

The number of solar panels used are rounded to 500 units and the number of batteries used are rounded to 15 units. This makes a final system of 285 kWp (500 x 570 Wp) solar power plant with 2.91 MWh (15 x 194 kWh) battery storage.

3.2. PVSyst Simulation

The solar PV system design simulation on PVSyst is divided into several different systems, namely grid-connected systems, stand-alone systems, and pumping systems, as confirmed by Aghaei et al [40]. For this study, a stand-alone system was used because of the lack of an electricity grid at the research site. The final parameter inputs on orientation and system are explained in Table 5.

Table 5. PV Panel Orientation

Parameters	***Value***
Plane Tilt	15˚
Azimuth	0˚

A plane tilt of 15° means that the angle between the plane of the PV panel and the horizontal state of the ground is 15° while an azimuth of 0° means that the PV panel is perfectly facing the southern hemisphere. These values are recommended by Mukisa and Zamora [41] to provide the best possible production of electricity in low latitude equatorial regions, similar to the location of this study.

To simulate the system, array losses are as follows. Array losses refer to the various factors that can reduce the overall efficiency and energy output of a solar photovoltaic (PV) array. These losses can occur for multiple reasons throughout the system, like wiring, component aging, shading, etc. This can result in reduced energy generation and imbalanced performance among the panels, as observed by Yang et al [42].

Table 6. Array Losses Input

Parameters	***Value***
Thermal Loss Factor	20 W/m^{2}K
DC Wiring Losses	0.5 % at STC
Light Induced Degradation	1.5 %
String Mismatch Loss	0.1 %
Serie Diode Loss	0.4 % at STC
Module Quality Loss	0.3 %
Module Mismatch Losses	2.0 % at MPP

In PVsyst, representation plays a crucial role in obtaining reliable and accurate results. The software provides a comprehensive database of solar panels, inverters, and batteries, allowing users to select the specific models and parameters that match the real-world components they are using. The structure of the system that is simulated is displayed in Figure 9. This schematical structure reveals the technical representation of the basic structure of solar grid in Figure 8, with 25 parallel strings of 20 PV modules in each array.

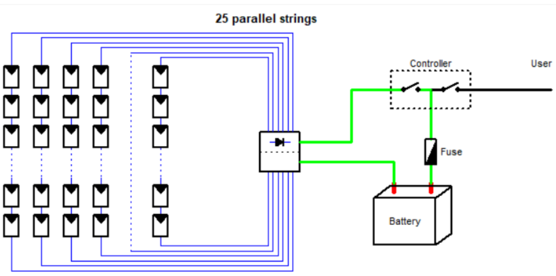

Figure 9. Schematical Structure of Simulated Solar Grid on PVsyst

Simulation on PVsyst gives several important results, such as normalized production and losses diagram. Monthly normalized production per kWp (kilowatt peak) is a metric used to evaluate the performance of a solar photovoltaic (PV) system over time by calculating the production of energy in kWh per kWp of the PV system each day, considering variations in solar irradiance and other factors. It helps provide a more accurate assessment of a solar system's output by accounting for the changing solar conditions throughout the year. This aspect is displayed in Figure 10.

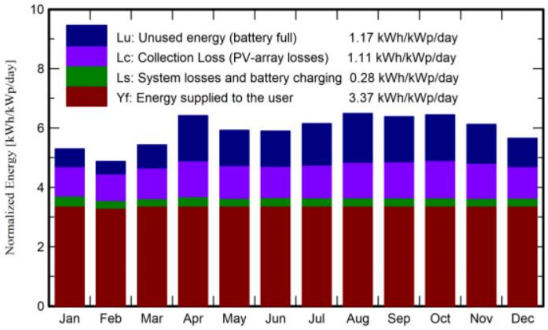

Figure 10. Normalized Production of the System

Figure 10 shows a bar chart that describes electricity production in kWh/kWp. The figure presents that the total energy supplied to the user is 3.37 kWh/kWp/day with total losses from PV-array, system, and battery charging of 1.39 kWh/kWp/day. This results in a total system efficiency of 70%.

Figure 11 shows the detailed losses of the PV system. It considers the array losses parameters in Table 6. The figure also reveals the estimated missing energy of the system, which is also synonymous with loss of load probability (LOLP). The LOLP of the system is estimated to be 0.17%. This is already lower than the Indonesian standard, which requires an electrical grid to have a LOLP below 0.274%. When referring to a low LOLP for a system, it means that the probability of experiencing an insufficient power supply is low, so it indicates a high level of reliability in meeting the electricity demand, as confirmed by Boroujeni et al [43].

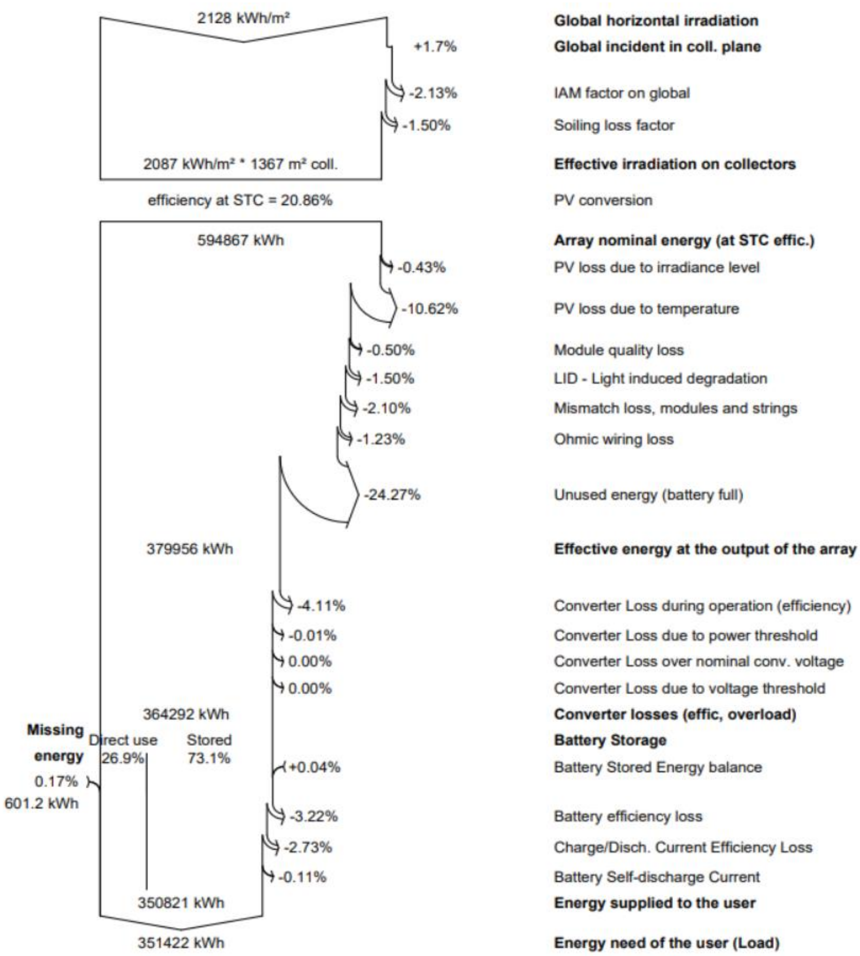

Figure 11. Losses Diagram of the System Simulated on PVsyst

3.3. Quasi-Dynamic Analysis

In a power system study, quasi-dynamic analysis refers to a method used to study and analyze the voltage profile in power systems. Gaitán et al [44] stated that it is an approximation technique that combines aspects of both steady-state and dynamic analysis to assess the voltage behavior over time. The quasi-dynamic analysis is conducted using DIgSILENT PowerFactory. The system voltage profile (per unit) is as below.

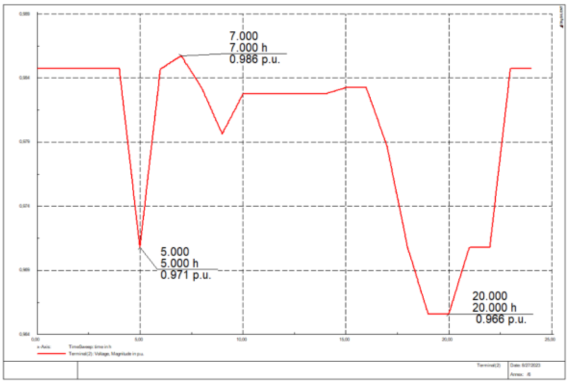

Figure 12. Voltage Profile of the System Simulated on DigSILENT PowerFactory

In the Definition and Classification of Power System Stability by Hatziargyriou et al [45], voltage drop can occur in an electric system when the electrical load increases. Voltage drop refers to the reduction in voltage levels between the power source (such as a utility grid or a generator) and the point of electrical load. It occurs due to the inherent resistance in the electrical conductors, such as wires and cables, that make up the distribution network.

When the load on an electrical system increases, more current flows through the conductors to power the additional devices or equipment. An increase in current results in a proportional increase in voltage drop due to the resistance of the conductors.

Figure 12 shows the voltage profile of the electrical system on the AC distribution side. The voltage of the system at maximum peak load at 8:00 p.m. is 96.6% of the nominal voltage. This means that the system is still at a very safe voltage according to standards (more than 90% and less than 110%) and meets the power system stability requirements, as confirmed by Ymeri et al [46].

3.4. Environmental Analysis

In PVsyst, CO_2 emission estimation is a feature that allows users to assess the environmental impact of a photovoltaic (PV) system by estimating the amount of carbon dioxide (CO_2) emissions reduced through the generation of renewable energy.

There are four results that can be analyzed: The total saving of CO_2 emissions in tons over the expected lifetime of the PV system, the annual reduction of CO_2 emissions, the reduction of CO_2 emissions per installed power, and the annual savings of CO_2 emissions per installed power. The simulation will compare CO_2 emission that is reduced by the PV system compared to Indonesian average grid emissions of 734 gCO_2/kWh. The result is as follows.

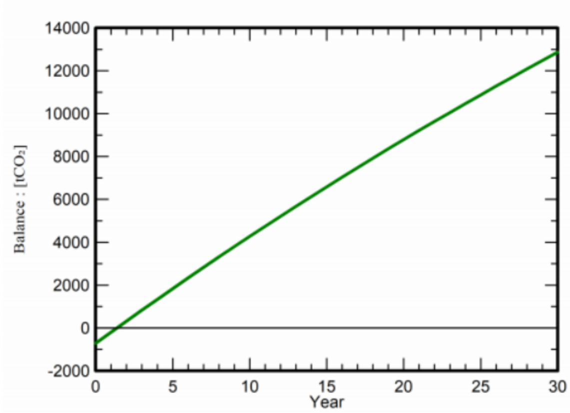

Figure 13. Total CO_2 Emission Reduction Simulated on PVsyst

Figure 13 shows total CO_2 emission reduction over the expected lifetime of the PV system with 1.5% annual degradation. It is calculated that the average annual reduction of CO_2 emission by the installation of this solar PV system is 398.897 tCO_2. This shows that the installation of the solar panel is in accordance with energy transition in reducing emission to address global warming.

4. Conclusions

Based on the simulation results, a 285 kWp solar power plant with 2.91 MWh of battery energy storage system (BESS) is considered necessary to ensure sustainable electricity on the island, which is estimated to consume 962,800 kWh daily. This result is close to the result of a simplified theoretical calculation, meaning that this study has contributed to significant findings in the form of proving that the calculation can be used as a fast method in estimating solar PV system sizing before doing simulation.

Using PVsyst and DIgSILENT Powerfactory, the LOLP of the system is estimated to be 0.17%, lower than the Indonesian standard that requires an electrical grid to have an LOLP below 0.274%. The voltage of the system in peak load is obtained at 96.6% of the nominal voltage that is a safe voltage according to standards. It is found that the combination of these two software can verify the designed PV-BESS system to be able to maintain the stability of the power system in accordance with applicable standards. The simulations have also shown the significant impact of battery energy storage systems (BESS) in addressing the vulnerability of electrical networks to insufficient electricity (loss of load) and voltage sags.

The field of off-grid solar design is dynamic and continually evolving, offering numerous avenues for future studies including newer energy storage solutions, load forecasting, policy review, and application of other software for power stability analysis. Overall, solar power generation system provides an efficient and reliable way to harness the power of the sun for practical use. The steps explained in this paper can be a guide for other renewable energy project planners to make a preliminary design of similar solar PV system, especially in isolated places with no electricity grid.

Acknowledgments

The author would like to thank colleagues at the School of Electrical Engineering and Informatics Institut Teknologi Bandung who provided insight and suggestions as well as Mr. Parlin Marbun for corrections.

Nomenclature

BESS	Battery Energy Storage System
GHI	Global Horizontal Irradiation (kWh/m^2)
HDI	Horizontal Diffuse Irradiation (kWh/m^2)
DNI	Direct Normal Irradiation (kWh/m^2)
PVOUT	Specific photovoltaic power output (kWh/kWp)
E_{LOAD}	Practical generated electricity (kWh)
η_s	PV system efficiency
η_{inv}	Inverter efficiency
η_{bat}	Battery efficiency
DOD	Depth of Discharge
psh	Peak Sun Hour (hours)
V_b	Battery voltage (V)
A_u	Autonomous days
P_{PV}	Maximum Power Output (kWp)
C_b	Battery capacity (Ah)
STC	Standard Test Condition
MPP	Maximum Power Point
LOLP	Loss of Load Probability (%)
LOLE	Loss of Load Expectation (hours/year)

References

[1] Aydin, M. J. R. e. (2019). Renewable and non-renewable electricity consumption–economic growth nexus: evidence from OECD countries. *Renewable Energy, 136,* 599-606. doi:10.1016/j.renene.2019.01.008

[2] Blimpo, M. P., & Cosgrove-Davies, M. (2019). *Electricity access in Sub-Saharan Africa: Uptake, reliability, and complementary factors for economic impact*: World Bank Publications.

[3] COP23. (2017). *COP23 Presidency Operations Manual*: UN Climate Change Conference.

[4] Jaiswal, K. K., Chowdhury, C. R., Yadav, D., Verma, R., Dutta, S., Jaiswal, K. S., & Karuppasamy, K. S. K. (2022). Renewable and sustainable clean energy development and impact on social, economic, and environmental health. *Energy Nexus, 7*, 100118. doi:10.1016/j.nexus.2022.100118

[5] Alshardy, A., Goodwin, S., & Liebman, A. (2021). *Data Visualisation for Remote Area Electrification Decision-Making: A Case Study of Indonesia.* Paper presented at the Proceedings of the twelfth ACM international conference on future energy systems.

[6] Likadja, F. J., Mauboy, E. R., & Leda, C. M. (2020). Prakiraan Kebutuhan Energi Listrik di Provinsi NTT Tahun 2019-2029 menggunakan Metode Gabungan dan LEAP. *Jurnal Media Elektro*, 20-28. doi:10.35508/jme.v0i0.2674

[7] Mustayen, A., Rasul, M., Wang, X., Negnevitsky, M., & Hamilton, J. (2022). Remote areas and islands power generation: A review on diesel engine performance and emission improvement techniques. *Energy Conversion and Management, 260,* 115614. doi:10.1016/j.enconman.2022.115614

[8] Nuttall, W. J., Mestel, B., & Dooley, L. S. (2019). Low carbon futures: Confronting electricity challenges on island systems. *Technological Forecasting and Social Change, 147,* 36-50. doi:10.1016/j.techfore.2019.06.014

[9] Kalbasi, R., Jahangiri, M., Nariman, A., & Yari, M. (2019). Optimal design and parametric assessment of grid-connected solar power plants in Iran, a review. *Journal of Solar Energy Research, 4*(2), 142-162. doi:10.22059/JSER.2019.282276.1114

[10] Amiroh, K., Widyantara, H., Setyawan, D. E., & Irzam, M. R. (2023). *Design and analysis of switching power vertical wind turbines and solar panels in the equatorial region.* Paper presented at the AIP Conference Proceedings.

[11] Alves, M., Segurado, R., & Costa, M. (2020). On the road to 100% renewable energy systems in isolated islands. *Energy, 198*, 117321. doi:10.1016/j.energy.2020.117321

[12] Sánchez, A. S., Junior, E. P., Gontijo, B. M., de Jong, P., & dos Reis Nogueira, I. B. (2023). Replacing fossil fuels with renewable energy in islands of high ecological value: The cases of Galápagos, Fernando de Noronha, and Príncipe. *Renewable and Sustainable Energy Reviews, 183*, 113527. doi:10.1016/j.rser.2023.113527

[13] Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Sustainable energy transition for renewable and low carbon grid electricity generation and supply. *Frontiers in Energy Research, 9*, 1032. doi:10.3389/fenrg.2021.743114

[14] Hannan, M., Faisal, M., Ker, P. J., Begum, R., Dong, Z., & Zhang, C. (2020). Review of optimal methods and algorithms for sizing energy storage systems to achieve decarbonization in microgrid applications. *Renewable and Sustainable Energy Reviews, 131*, 110022. doi:10.1016/j.rser.2020.110022

[15] Steffen, B., Beuse, M., Tautorat, P., & Schmidt, T. S. (2020). Experience curves for operations and maintenance costs of renewable energy technologies. *Joule, 4*(2), 359-375. doi:10.1016/j.joule.2019.11.012

[16] Ghadimi, N., Sedaghat, M., Azar, K. K., Arandian, B., Fathi, G., & Ghadamyari, M. (2023). An innovative technique for optimization and sensitivity analysis of a PV/DG/BESS based on converged Henry gas solubility optimizer: A case study. *IET Generation, Transmission & Distribution*. doi:10.1049/gtd2.12773

[17] Al-Saffar, M., & Musilek, P. (2020). Reinforcement learning-based distributed BESS management for mitigating overvoltage issues in systems with high PV penetration. *IEEE Transactions on Smart Grid, 11*(4), 2980-2994. doi:10.1109/TSG.2020.2972208

[18] Kumar, N. M., Subathra, M. P., & Moses, J. E. (2018). *On-grid solar photovoltaic system: components, design considerations, and case study.* Paper presented at the 2018 4th International Conference on Electrical Energy Systems (ICEES).

[19] Lakshika, K. H., Boralessa, M. K. S., Perera, M. K., Wadduwage, D. P., Saravanan, V., & Hemapala, K. M. U. (2020). Reconfigurable solar photovoltaic systems: A review. *Heliyon, 6*(11).

[20] Naderipour, A., Ramtin, A. R., Abdullah, A., Marzbali, M. H., Nowdeh, S. A., & Kamyab, H. (2022). Hybrid energy system optimization with battery storage for remote area application considering loss of energy probability and economic analysis. *Energy, 239*, 122303. doi:10.1016/j.energy.2021.122303

[21] Yin, J., Molini, A., & Porporato, A. (2020). Impacts of solar intermittency on future photovoltaic reliability. *Nature Communications, 11*(1), 4781. doi:10.1038/s41467-020-18602-6

[22] Khalkho, A. M., Rapada, B., Majumder, G., Cherukuri, M., & Mohanta, D. K. (2022). Impact assessment of solar power generation uncertainty on smart grid reliability and carbon neutrality. *Frontiers in Energy Research, 10*, 851449. doi:10.3389/fenrg.2022.851449

[23] Sulaiman, S. I., Ab Majid, H., & Othman, Z. (2022). Loss of load probability minimization for stand-alone photovoltaic system using elephant herding optimization. *Energy Reports, 8*, 1038-1044. doi:10.1016/j.egyr.2022.05.278

[24] Kumar, R., Rajoria, C., Sharma, A., & Suhag, S. (2021). Design and simulation of standalone solar PV system using PVsyst Software: A case study. *Materials Today: Proceedings, 46*, 5322-5328. doi:10.1016/j.matpr.2020.08.785

[25] Satish, M., Santhosh, S., & Yadav, A. (2020). *Simulation of a Dubai based 200 KW power plant using PVsyst Software.* Paper presented at the 2020 7th International Conference on Signal Processing and Integrated Networks (SPIN).

[26] Salmi, M., Baci, A. B., Inc, M., Menni, Y., Lorenzini, G., & Al-Douri, Y. (2022). Desing and simulation of an autonomous 12.6 kW solar plant in the Algeria's M'sila region using PVsyst software. *Optik, 262*, 169294. doi:10.1016/j.ijleo.2022.169294

[27] Thotakura, S., Kondamudi, S. C., Xavier, J. F., Quanjin, M., Reddy, G. R., Gangwar, P., & Davuluri, S. L. (2020). Operational performance of megawatt-scale grid integrated rooftop solar PV system in tropical wet and dry climates of India. *Case Studies in Thermal Engineering, 18*, 100602. doi:10.1016/j.csite.2020.100602

[28] Zhao, C., Guo, L., Zhang, X., & Chi, Y. (2019). Optimization Design of Building Integrated Photovoltaic System with LOLP Algorithm. *International Journal of Performability Engineering, 15*(2), 645. doi:10.23940/ijpe.19.02.p29.645653

[29] Starčević, V., Zeljković, Č., Kitić, N., Mršić, P., Erceg, B., & Jovanović, V. (2021). *PV system integration assessment by automated Monte*

Carlo simulation in DIgSILENT PowerFactory. Paper presented at the 2021 20th International Symposium INFOTEH-JAHORINA (INFOTEH).

[30] Zare Oskouei, M., & Mohammadi-Ivatloo, B. (2020). Modeling and Optimal Operation of Renewable Energy Sources in DIgSILENT PoweFactory. *Integration of Renewable Energy Sources Into the Power Grid Through PowerFactory*, 51-81.

[31] Hassan, Q. (2021). Evaluation and optimization of off-grid and on-grid photovoltaic power system for typical household electrification. *Renewable Energy, 164*, 375-390. doi:10.1016/j.renene.2020.09.008

[32] Hayes, B. P., Thakur, S., & Breslin, J. G. (2020). Co-simulation of electricity distribution networks and peer to peer energy trading platforms. *International Journal of Electrical Power & Energy Systems, 115*, 105419. doi:10.1016/j.ijepes.2019.105419

[33] Luo, X., Liu, Y., Liu, J., & Liu, X. (2019). Optimal design and cost allocation of a distributed energy resource (DER) system with district energy networks: A case study of an isolated island in the South China Sea. *Sustainable Cities and Society, 51*, 101726. doi:10.1016/j.scs.2019.101726

[34] Sari, L., Rauzi, E., & Mahmud, M. (2021). *Sun-path model as a simple helping tool for architecture students in understanding saving energy building design.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

[35] Khatib, T., Mohamed, A., & Sopian, K. (2013). A review of photovoltaic systems size optimization techniques. *Renewable and Sustainable Energy Reviews, 22*, 454-465. doi:10.1016/j.rser.2013.02.023

[36] Ibrahim, K. H., Hassan, A. Y., AbdElrazek, A. S., & Saleh, S. M. (2023). Economic analysis of stand-alone PV-battery system based on new power assessment configuration in Siwa Oasis–Egypt. *Alexandria Engineering Journal, 62*, 181-191. doi:10.1016/j.aej.2022.07.034

[37] Abubakar, A., & Almeida, C. F. M. (2020). *Analysis of Battery Energy Storage System Sizing in Isolated PV Systems Considering a Novel Methodology and Panel Manufacturers Recommended Methodology.* Paper presented at the 2020 IEEE PES Transmission & Distribution Conference and Exhibition-Latin America (T&D LA).

[38] Lo Franco, F., Morandi, A., Raboni, P., & Grandi, G. (2021). Efficiency comparison of DC and AC coupling solutions for large-scale PV+ BESS power plants. *Energies, 14*(16), 4823. doi:10.3390/en14164823

[39] Ali, M. M. E., & Salih, S. K. (2013). A visual basic-based tool for design of stand-alone solar power systems. *Energy Procedia, 36*, 1255-1264. doi:10.1016/j.egypro.2013.07.142

[40] Aghaei, M., Kumar, N. M., Eskandari, A., Ahmed, H., de Oliveira, A. K. V., & Chopra, S. S. (2020). Solar PV systems design and monitoring. In *Photovoltaic Solar Energy Conversion* (pp. 117-145): Elsevier.

[41] Mukisa, N., & Zamora, R. (2022). Optimal tilt angle for solar photovoltaic modules on pitched rooftops: A case of low latitude equatorial region. *Sustainable Energy Technologies and Assessments, 50*, 101821. doi:10.1016/j.seta.2021.101821

[42] Yang, B., Li, W., Zhao, Y., & He, X. (2009). Design and analysis of a grid-connected photovoltaic power system. *IEEE Transactions on Power Electronics, 25*(4), 992-1000. doi:10.1109/TPEL.2009.2036432

[43] Boroujeni, H. F., Eghtedari, M., Abdollahi, M., & Behzadipour, E. (2012). Calculation of generation system reliability index: Loss of Load Probability. *Life Science Journal, 9*(4), 4903-4908. doi:10.7537/marslsj090412.736

[44] Gaitán, L. F., Gómez, J. D., & Rivas-Trujillo, E. (2019). Quasi-Dynamic Analysis of a Local Distribution System with Distributed Generation. Study Case: The IEEE 13 Nodes System. *TecnoLógicas, 22*(46), 140-157. doi:10.22430/22565337.1489

[45] Hatziargyriou, N., Milanovic, J., Rahmann, C., Ajjarapu, V., Canizares, C., Erlich, I., . . . Pal, B. (2020). Definition and classification of power system stability–revisited & extended. *IEEE Transactions on Power System, 36*(4), 3271-3281. doi:10.1109/TPWRS.2020.3041774

[46] Ymeri, A., Dervishi, L., & Qorolli, A. (2014). *Impacts of Distributed Generation in Energy Losses and voltage drop in 10 kV line in the Distribution System.* Paper presented at the 2014 IEEE International Energy Conference (ENERGYCON).