



School of Information Technology and
Engineering at the ADA University



School of Engineering and Applied Science
at the George Washington University

OPERATION OF BATTERY STORAGE SYSTEMS IN AUXILIARY SERVICES
AND BALANCING MARKETS IN THE ELECTRICITY MARKET

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THESIS ACCEPTANCE

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ABSTRACT

The battery storage systems (BSS) will be an integral part of solving the challenges caused by increasing the penetration of renewable energy sources into modern grids. In this respect, these systems will stabilize the grid not only in frequency and voltage fluctuations but also increase energy reliability and economic efficiency. The present work puts its focus on the integration of BSS in standalone and grid-connected PV systems, covering its design, operation characteristics, and economic impacts of such integration. Advanced simulation tools like PVsyst are being used in investigating and optimizing systems through load profiles and meteorological conditions, including specifications that concern the equipment.

The present research has found out the functions of BSS in allowing resilience and flexibility of the grids. With the help of BSS, stand-alone systems ensure that the power supply remains continuous in conditions of low solar irradiance, and for those using grid-connected systems, these ensure energy management efficiency with the purpose of peak shaving. BSS applications are far broader than energy storage and include issues like frequency and voltage regulation, improving grid resilience through blackouts, and economic advantage in terms of peak shaving and arbitrage; they have numerous applications and implications within current power systems.

The key findings have proved that lithium-ion batteries, due to their high energy density, fast response, and declining prices, are the most suitable for BSS applications. Besides this, the inclusion of tracking systems and optimized PV array orientations enhances energy capture efficiency. The study also covers the latest developments in other battery technologies, such as solid-state and sodium-ion batteries, which have demonstrated the potential to overcome cost and efficiency barriers.

Economic analysis underlines the viability of BSS in both stand-alone and grid-connected configurations, while life-cycle cost analyses have shown that these systems are cost-effective in the long term. The environmental benefits are reflected in reduced carbon emissions and increased renewable energy use. Challenges include battery degradation, high upfront costs, and regulatory barriers. Scaling up BSS adoption will require addressing these challenges through policy support, technology advancement, and innovative system designs.

This study adds to the growing knowledge in the integration of renewable energy, and from the results, it gives actionable recommendations to improve system performance, further cost-efficiency, and sustainability. The findings highlight the potential transformation of BSS to shape the future of energy systems by paving the way for an energy transition that is both sustainable and resilient.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
AC	Alternating Current
BSS	Battery Energy Storage Systems
DC	Direct Current
DOD	Depth of Discharge
GND	Ground
ISC	Short Circuit Current
LOLP	Loss of Load Probability
MPPT	Maximum Power Point Tracking
PR	Performance Ratio
PSH	Peak Sun Hours
PV	Photovoltaic
QTY	Quantity
RMS	Root Mean Squared
RES	Renewable Energy Sources
SOC	State of Charge
SPV	Solar Photovoltaic
VOC	Open Circuit Voltage

CHAPTER ONE

INTRODUCTION

Problem Statement

The transition to renewable energy sources, like solar and wind, is particularly important from a global sustainability perspective and low carbon emissions. The intermittency of these resources inherently provides major challenges with regard to grid stability, reliability, and economic efficiency. In the absence of proper storage solutions, energy surpluses during peak generation and deficits during high demand cannot be effectively managed. These challenges have been mitigated recently with the emergence of Battery Energy Storage Systems. The BSS have facilitated the stabilization of the load curve, frequency, and voltage regulation, as well as peak shaving, and make for one of the vital elements in modern power systems. In contrast, such barriers as high costs, degradation of batteries, and regulatory challenges require an in-depth evaluation of technical and economic feasibility.

Motivation

The motivation of this research has been the critical and urgent need for optimization in integrating BSS into energy systems, allowing fast-growing penetration of RES. Applying advanced simulation tools, this research will investigate the potential of BSS in enhancing energy reliability, grid resilience, and economic efficiency. These will also provide useful insights related to the design and operation of BSS within auxiliary services and balancing markets.

Scope and Aim of the Study

This study assesses the role of BSS in modern energy systems, focusing on their applications within the following:

1. Frequency and voltage regulation
2. Energy arbitrage and peak shaving
3. Grid resilience and economic optimization

Three case studies, simulated by the PVsyst software, were conducted for this purpose:

- Standalone PV-BSS system for rural applications
- Grid-connected PV-BSS system with surplus energy integration
- Comparative techno-economic performance metrics of the two systems

The study focuses on system design optimization and investigates the main indicators like energy reliability, economic viability, and operational efficiency of the studied systems, while building recommendations on scaling BSS in different energy systems.

Significance of the Study

These functionalities of BSS address a number of operational challenges related to the integration of RES and have manifold benefits in gridding during periods of high renewable penetration, energy reliability, and hence contribute to economic goals by peak shaving and ancillary services. The present research forms part of a wide range of scholarly contributions in the area of renewable energy integration and proposes a simulation-based framework aimed at enhancing the performance and scalability of BSS. The present research will help the policymakers, energy professionals, and researchers take a call on the adoption of sustainable and economically viable energy solutions.

Limitations of the Study

A few limitations are considered while carrying out simulation-based analyses for the present study. Simplified meteorological and load data are used that may not capture real-time variability. Idealized battery performance assumptions: Excluding long-term degrading effects. It also does not deeply capture regulatory and market-specific barriers. The aforementioned limitations show several avenues for further research that will be required to validate these findings through real-world applications and advanced modeling techniques.

CHAPTER TWO

LITERATURE REVIEW

Overview of Battery Storage Systems in Electricity Markets

The use of condensed Battery Storage Systems (BSS) in modern electricity markets is already an integral part of the ability to deal with problems that are due to the fact that the energy suppliers have gone more and more towards renewable energy sources (RES). As the deficiencies in RES are actually intermittent, BSS can address grid reliability, operation, and this is through their provision of flexibility as well as the generation of efficient energy management. In this chapter, various sources of literature were researched on BSS developments, applications, and simulation and optimization tools using PVsyst and HOMER software were investigated.

2.1 Role of BSS in Modern Power Grids

The evolution in power grids from a centralized system to a distributed network increases the need for flexibility and ancillary services. Traditional power plants have been providing such services like frequency control and load balancing; however, increasing integration of RES needs alternative ways.

Kumar et al. (2020) indicate that BSS can solve problems from grid instability due to changes in renewable energy and offer services such as frequency regulation, peak shaving, and voltage control [4]. Kryonidis et al. (2021) also point out the technological trends of BSS in active distribution networks and show how they can offer extra services to keep the grid stable [19].

2.2 Auxiliary Services Provided by BSS.

Auxiliary services become a must for the credible sustenance of grid operation. BSS stands among the best in terms of response time and scalability:

1. Frequency Regulation: BSSs are considered in the main in relation to Frequency Controlling Reserve, a kind of application responsible for maintaining the deviations in grid frequency within the limits provided. It offers a ground for fact since the BSSs seem suitable for application in FCR because they can quickly charge/discharges at frequency variations according to the study in Balancing Group Deviation in 2024 [3]. That's what enables the SoC-operational flexibility given by the DOF to make the BSS operator operate parallel to FCR market participation with maintained profitability and compliance of the grid.

2. Voltage Regulation: Increase in RES share is one of the major concerns regarding voltage imbalance. BSS can provide dynamic reactive power capacity for voltage stability at both transmission and distribution levels [19].

3. Load Balancing and Peak Shaving: Battery storage systems can help in the managing of load and at the same time reduce congestions on the grid to ensure a supply-demand balance. Li et al., in 2020, have shown that the coordinated control strategy of BSS can effectively shave peaks and support black start operations [19].

4. Energy Arbitrage: BSS is able to store excess energy during the low-cost period and discharge during peak demands for maximum economic benefit in the low-cost period. It thus enables the balance market requirement whereby energy deviations must be resolved according to market prices [11].

2.3 Participation of BSS in Balancing Markets

Balancing markets clear the supply and demand in real time. BSS have emerged as competitive players owing to the fact that they can provide fast response services.

In Germany, for example, balancing energy is dispatched at 15-min intervals, and deviations of contracted energy flows are remunerated with imbalance settlement prices. It is concluded that battery storage operators use intraday trading and SoC management optimally to participate in the balancing markets in order to maximize revenues [14]. Thien et al. (2024) proved that FCR supplied by BSS flexibility can indeed grasp additional profits while keeping the grid compliant [15].

2.4 Economic and Environmental Benefits of BSS

The implication of BSS makes a lot of economic and environmental sense.

1. **Cost-Effectiveness:** According to Masood et al., 2024, hydrogen batteries compared with lithium-ion ones on rooftop solar PV systems exhibit higher numbers when it comes to longevity due to their almost negligible degradation rate [1]. Certain economic studies cited suggest that, due to their relatively short payback period, lithium-ion batteries are better suited to shorter-duration storage [13].

2. **Environmental Benefits:** BSS would help in reducing the level of emissions by the fact that renewable resources can be brought into the cycle of energy flow. According to Hassan et al., 2024, there are no carbon emissions from hydrogen-based system operations; however, water and heat will be produced during the operation as by-products only [1].

3. **Cost Competitive:** The progressive decrease in the costs of BSS technology and associated materials as the development in this particular field advances. Innovations in the designs for better heat exchangers in CAES helped in a reduction of their costs, according to Kowalczyk, 2022 [6].

2.5. Challenges in BSS Deployment

Despite they have many advantages, Battery storage systems face several obstacles that need to be mentioned:

1. **Degradation and Lifespan:** Battery performance degrades with increased charge-discharge cycles. Lithium-ion batteries, for example, degrade much faster compared to hydrogen batteries, which makes the difference between batteries their feasibility for a long period of time [13].

2. **High Upfront Costs:** One of the biggest impediments to the implementation of BSS is its huge upfront cost. Yet, with efficiency improvement and cost reduction, it is gradually becoming economically viable [16].

3. **Regulatory and Market Challenges:** With increasing utilization, existing policies and market arrangements will have to adjust to the rise of BSS in the electricity market. IRENA, 2019, points to policy enablement to facilitate deployment on the front of distributed energy resources and the integration of battery systems [5].

2.6. Case Studies

The following are case studies on the use and benefits of BSS in cooperative projects and in market regulation:

1. Germany: Regular reserves are generated using BSS in Germany, and trades are settled within the same day of the unit split. The M5BAT project demonstrates the technical and economic feasibility of using BSS in a fair market [14].

2. Azerbaijan: Recently, Azerbaijan has been trying to implement a renewable energy policy, which means that the country will improve grid stability in line with other measures by introducing BSS into the national electricity exchange system. The Nakhchivan solar power plant offers many opportunities for research in renewable energy.

3. Australia: BSS application in power arbitration and load balancing is a practical and effective solution for solar PV systems. Economically, the benefits of using Li-ion batteries in this application are based solely on the residential level and were demonstrated by Hassan et al., (2024).

2.7. Reviews from different papers

Parvathy Suresh et al., (2014) examined the performance of photovoltaic (PV) systems, considering factors like solar radiation, temperature, and wind speed. Their research focused on designing standalone PV systems in Thiruvananthapuram, accounting for field losses and non-uniform operating conditions.

By analyzing factors such as temperature, dirt, seasonal changes, partial shading, system voltage, and aging, the team simulated the total energy demand of 7468 watt-hours using PVsyst software. They also explored how material technology, production processes, and shading impact system performance. PVsyst provides detailed analysis of various loss types, using appropriate models for system components and known loss sources.

The study highlights uncertainties related to meteorological data, PV module models, and the accuracy of manufacturer specifications.

Y.M. Irwin et al., (2015) report the depletion of conventional energy sources and its impact on the climate require an urgent call for replacement power sources to meet the current power requirement. The reportable analysis summarizes the style aspects and evaluations of the SPV system and supports real field trials in a 1kW off-grid photovoltaic energy system. Power Generation, radiation and performance-assisted analyses are evaluated using PVsyst. The small roof-top system and its performance-assisted analysis was evaluated using the PVsyst tool. It uses radiation information to calculate the power generated, the power used and the unused power. This system was installed at Jamia Millia Islamia, New Delhi, India.

Priya Yadav et al. note that PV systems work satisfactorily in regions that receive ample sunlight. Hamirpur was reportedly receiving a reasonable amount of radiation, with an average daily solar radiation of 4.4 kilowatt-hours per square meter. A 1-kilowatt peak PV system was specially designed for Hamirpur using the PVsyst software and local weather data. The performance ratio, one of the most significant overall parameters, was found to be 0.724 for the entire year, concluding satisfactory performance. Thus, PV systems can be suggested as one of the feasible sources of power generation for Hamirpur. Results show evidence that larger-scale solar PV systems can be designed for the area.

C.P. Kandasamy et al., (2013) carried out the simulation of grid-connected solar photovoltaic (PV) systems with the help of software called PVsyst. They had estimated overall losses in photovoltaic power generation due to temperature, internal network, and power electronic losses and also the performance ratio of systems. In this paper, a 1 MW PV system has been considered to assess the life cycle cost and solar potential in different locations in southern Tamilnadu. The best site selection was determined by making a comparison between performance ratio, energy production, and cost.

Rashid Srivastava et al., (2017) explained that computer software is needed for the estimation of the expected output from the solar power system. They had designed a grid-connected solar panel system with the help of a software called PVsyst. In this research paper, the installation, energy output, and possible losses of the system have been optimally performed.

By simulating different configurations they identified the optimum size of the solar system to meet the demand of the college electricity reliably. PVsyst helped to determine some factors like panel efficiency, energy production, and system losses. The outcome of the study revealed that the system with 2000 solar panels with a rating of 250 watts plus an inverter of 50 kW is most ideal. It will yield about 901.44-megawatt hours annually with an efficiency estimation of about 83.1%.

Sujoy Barua et al., (2017) also conducted research on the design and potential of a University Campus solar power system in the year 2017. He did the modeling of the system performance with the help of software known as PVsyst, which had taken factors into consideration like weather and the energy demand of the campus.

The result of the simulation demonstrated that the amount of electricity generated by the system was about 580 megawatt hour during a year. This was approximately 10% of the University's campus energy usage. They chose a method of implementing the solar power system with possibilities of fulfilling the demands of the university in order to make things greener.

Kenneth E. Okedu et al., (2014) HOMER is a micro power optimization model that simplifies the process of assessing the feasibility of both off-grid and on-grid power systems for a wide range of applications. In this paper, the authors have done the designing and analysis of hybrid power systems including conventional generators, cogeneration, wind turbines, solar PV, hydropower, batteries, energy units, biomass, and a mix of different information sources by using HOMER Hybrid Optimization Modeling Software. This paper is organized into two major sections, namely the main section and the analysis section. The first part is devoted to a detailed discussion on measurement of power efficiency and production of sustainable energy. In the second part, a complete case study is presented by considering two cases with two different load profiles. It has been proved that stack profile affects the framework of sustainable power supply and the gear types lead to revenue loss.

In a paper released in 2015, **Punyashree Pattanayak** and her colleagues explained the creation of a hybrid wind and solar energy system for remote area, which has been optimized with the help of the software called HOMER and the economic model applied integrated modeling for each solution space. He said that the costs of performance of each component including the standby diesel generator were also considered in the study. The hybrid system is able to store and supply the electricity where a wind and solar generation is available in regions where there are dense population. With regard to rural households, the researchers noted that their load filing is different from the urban one as the variability is less. They also emphasized the economic advantages of hybrid systems in areas far from the grid and with high costs of fuel delivery.

Prashant Kumar and colleagues (2015) designed and simulated independent hybrid systems to power isolated ATMs. Their main objective was to seek ways to mitigate the energy crisis on a global scale. Noticing that energy usage is on the rise and that fossil fuels are limited, they targeted distributed generation, especially solar and wind. All these renewables, supplemented with a diesel generator as a standby, can be economical and dependable on-site power solutions. This study sought to optimize the use of renewables while also attempting to reduce total cost of the system.

Samira Salahi et al., (2016) In one of her projects, she along with her team also developed a microgrid system for a village that is endowed with rich solar and wind resources. We simulated six scenarios in order to decide the most optimal design. Their conclusions show that a partially Offgrid microgrid which is connected to the grid is the best.

Moreover, they also performed a sensitivity study which aimed to incorporate the effects of other variables as interest rates, prices, fuel costs, wind, solar radiation and air temperature. The results reveal that when global fuel prices or interest rates reach high level, the renewable energy sources are cheaper than diesel generators. Also, it is cheaper to use diesel generators in conjunction with other renewable sources of energy to generate electricity than to buy from the grid.

Sunanda Sinha et al., (2014) explained in their very important paper, Sinha and his colleagues (2014) recommend the application of techno-economic analysis for Renewable Energy systems. This is because the design of multi-generation hybrid systems is rather complicated requiring a toolkit that specialized software such as HOMER, Hybrid2, etc. There is therefore logical basis for the article which seeks to discuss the features of these tools, their design, analysis, optimization, and economic evaluation capabilities. This information can help researchers to pick up the most appropriate tool based on their design requirements.

Rashid Srivastava et al., (2016) The need for renewable energy generation, as noted by Rashid Srivastava and his team (2016), is driving the increasing demand for electricity worldwide. A promising approach to reduce reliance on conventional energy sources is the use of hybrid grid-independent renewable energy systems. To ensure a reliable, efficient, and cost-effective energy supply, it is crucial to optimize these systems' components and costs. HOMER software was utilized to simulate and model a hybrid system that included photovoltaic panels, wind turbines (VGAS), converters, diesel generator blades from HPC, and other components. The system's ability to perform and withstand different conditions was evaluated as an indication of potential improvements.

The reviewed literature underlines the transformative role of BSS in modern energy systems. These systems not only address the challenges of integrating renewable energy sources but also improve grid stability and operational flexibility. Simulation tools such as PVsyst and HOMER provide critical information about system optimization by providing efficient and sustainable energy management. Add to that the continuous decline in costs, whereas development in some areas related to core technologies, such as solid-state batteries and artificial intelligence-oriented management systems, has given a significant boost to the global adoption of BSS. Correspondingly, the policy frameworks for supporting the integration of renewables and increasing the emphasis on carbon emission reduction further underlines the indispensable role of BSS in energy transition. BSS stands at the juncture of shaping the future of flexible and green energy systems globally by overcoming the twin existing obstacles of high start-up cost and regulatory challenges.

CHAPTER THREE

RESEARCH APPROACH OR METHODOLOGY

3.1 Data Collection

Data collection was an important first step since it provided a basis for further research. Hence, this part explains how data was gathered and whether the final created system is in line with the project's requirement and environmental conditions.

Evaluation of Site

Area: Nakhchivan Solar Power Plant was selected due to its high solar potential. Environmental conditions are good, hence this area is suitable for the installation of a standalone solar SPV system.

Reasons: Lots of sunlight throughout the day ensures high energy generation.

Analysis of Energy Demand

Procedure: Energy demand needs of the temporary campsite were determined through detailed analysis.

Input Parameters:

Number of hours of operation
Kinds of appliances and equipment used
Power consumption rates

Output: Daily load profile estimation with a high degree of accuracy for reliability.

Meteorological Data Acquisition

Sources: The data was available from the meteorology station located at Nakhchivan Solar Power Plant and from online reliable databases.

Parameters Collected:

- Solar radiation levels
- Ambient temperature
- Wind speed

Importance: All these variables have a tremendous influence on the performance and optimization of SPV systems.

Constraint Analysis

Objectives: To determine space availability for system installation. To establish the structural constraints of the temporary structure.

To establish systems' autonomy needs, which were stated as the number of days that the system goes without direct sunlight.

3.2 Data Analysis

This phase involved the translation of raw data into useful parameters that shall help in the systems design. Detailed modeling and analysis using the PVsyst software had been performed.

Load Profile Development

1. Input: Temporary structure energy consumption patterns data.
2. Process:
 - Develop hourly and daily patterns of electricity use.
 - Determine peak demand load requirements.
 - Calculate seasonal difference in overall energy consumption.
3. Output: In-depth knowledge of what should be provided.

Meteorological Data Interpretation

1. Variables Considered:
 - Solar radiation
 - Seasonal variations in radiation
 - Time of the day of the peak solar radiation
2. Objective: To optimize the arrangement of the photovoltaic system to achieve maximum energy capture efficiency.

PVsyst System Modeling

1. Input parameters:
 - System autonomy desired
 - Daily energy consumption
 - Capacity of batteries and photovoltaic array
2. Process:
 - Enter data gathered into PVsyst.
 - Simulation of Energy Production, Battery Behaviour, and System Performance for Various Conditions

- Run various design options to determine possible bottlenecks.
3. Output: Detailed simulation results to aid decision-making.

Data Interpretation and Visualization

1. Tools: Graphs and tables from PVsyst.
2. Focus on:
 - Power generation trend
 - System behavior regarding various environmental and functional factors
 - Possible optimization opportunities

3.3 Process Flowchart and Algorithm Description

Flowchart

The flowchart below is the methodology to be followed:

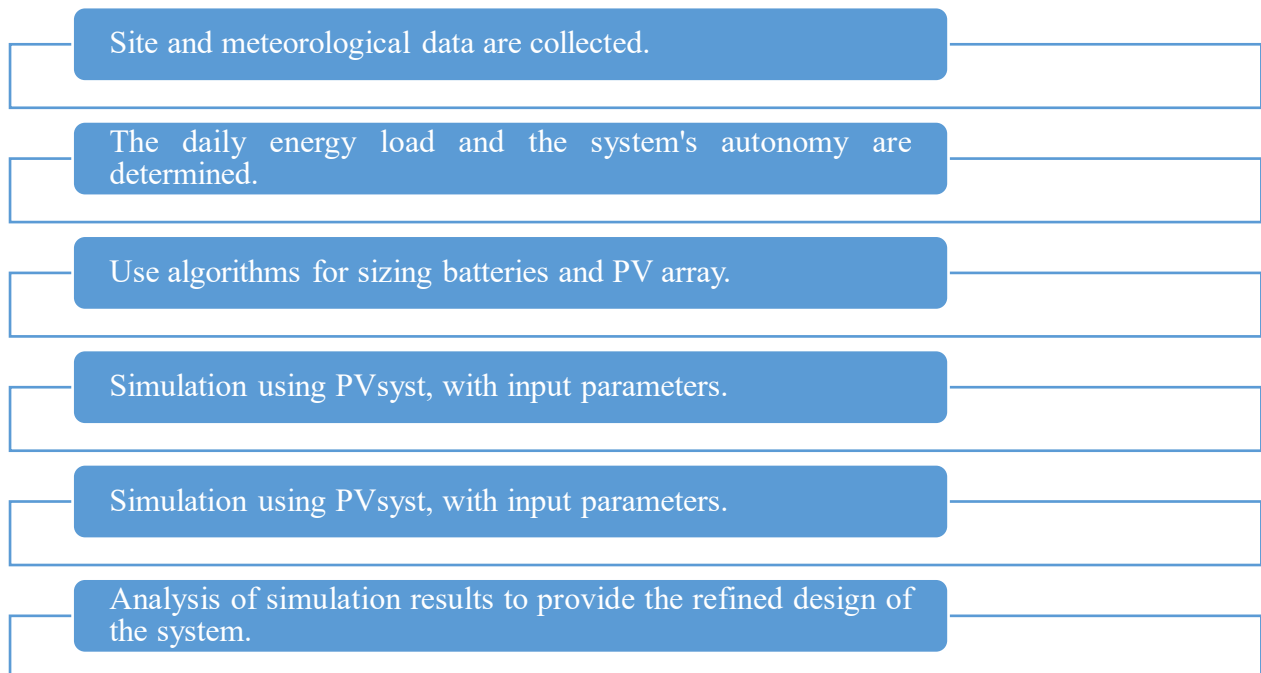


Figure 3.1: Methodology Procedure.

Algorithm Descriptions

1. Battery Sizing Algorithm

- Input: days of autonomy, DOD, and battery voltage.
- The weighted operating time for the whole house is calculated as:

$$t = \frac{288 \times 4 + 1800 \times 8 + 160 \times 4 + 1200 \times 10 + 250 \times 0.5 + 4503 \times 2 + 240 \times 2 + 3000 \times 3}{9240} = 3.2 \text{ hours/day} \quad (3.1)$$

The required battery output depends on the load requirements of the system and the autonomy period. It can be calculated using the following formula:

$$B_{\text{out}} = \frac{E_{\text{daily}} \times T_a}{V_{\text{dc}}} \quad (3.2)$$

Where E_{daily} is the daily energy consumption and T_a is the autonomy, V_{dc} is DC voltage. In this system, the daily energy consumption is 9240 Wh, autonomy is 4 days and DC voltage is 51.8V. Battery output:

$$B_{\text{out}} = \frac{9240 \times 4}{51.8} = 713 \text{ Ah}$$

Depth of Discharge (DOD): Most lithium-ion batteries allow for 80-90% DOD. For this design, 90% DOD is used, making the adjusted capacity:

$$B_{\text{adjusted}} = \frac{713}{0.9} = 792 \text{ Ah.} \quad (3.3)$$

2. PV Array Sizing Algorithm

Input: peak sun hours, and system efficiency.

Equation: The exact tilt angle can be determined from the formula:

$$\delta = 23.45 \sin \left[\frac{360}{365} (284 + n) \right] \quad (3.4)$$

where, (n) is the number of the day in the year.

It should provide the battery with more energy in order to support the loads.

$$I = \frac{E_{\text{crit}}}{\eta_B \times V_{\text{dc}} \times t_{\text{PSH}}} \quad (3.5)$$

E_{crit} is the daily energy consumption during the critical design month, η_B is the battery's charge efficiency, V_{dc} is the system voltage, and t_{PSH} is the peak sun hours for the critical design month. In this analysis, the critical design month will be February, and the battery efficiency will be taken as 90%. From the table, the current will be calculated as:

$$I = \frac{9240}{0.9 \times 51.8 \times 5.75} = 35.89 \text{ A}$$

With consideration for soiling, the rated array output current can be estimated by:

$$I = \frac{I_{arr.}}{C_s} \quad (3.6)$$

I_{array} in the above equation is required current and C_s is soiling coefficient. In this case the rated current is then calculated as:

$$I = \frac{35.89}{0.9} = 39.88A$$

The rated voltage of the array will be given by the formula:

$$V_{rat.} = 1.2 \times V_{DC} \times \{1 + [C_{\%V} \times (T_{maximum} - T_{reference})]\} \quad (3.7)$$

Where V_{DC} is the direct current voltage, $C_{\%V}$ is the temperature coefficient, $T_{maximum}$ is the maximum operating temperature, and $T_{reference}$ is the reference temperature. Then the array voltage should be calculated using above formula:

$$V_{rated} = 1.2 \times 51.8 \times \{1 + [0.0045 \times (50 - 25)]\} = 67.19V$$

Grid-connected System AC Energy Needs

The system's AC energy needs are determined by the following equation:

$$365 \times S \times P_{DCpeak} \times \eta = E_{ac} \quad (3.8)$$

Where:

S = Peak Sun Hours for the location (5.42PSH)

P_{DCpeak} = Peak DC power system rating (in watts per W_p)

η = Overall system efficiency from PV to AC grid (typically 75%)

For the project, the annual AC energy production per W_p installed is:

$$E_{ac} = 365 \times 5.42 \times 1 \times 0.75 = 1.48 \text{ kWh}$$

Given the monthly AC load of 277.2kWh, the yearly consumption is:

$$277.2 \times 12 = 3,326.4 \text{ kWh}$$

The required system DC power output is calculated as:

$$P_{DCpeak} = 3,326.4 / 1.48 = 2,247.57 \text{ Wp}$$

Photovoltaic Module Selection

A high-efficiency module will be used in this grid-connected system: LG 400N2T-A5

To satisfy the required DC power of 2,247.57Wp, the number of modules required is:

$$\text{Number of Modules} = 2,247.57 / 400 = 6 \text{ modules (rounded up)}$$

3. Economic Analysis Algorithm

- Equation
- Where in: Initial cost, Maintenance cost at present value, Replacement cost at present value, Salvage value

Cost Analysis

4.6.1.1 Initial Costs

Initial costs include all costs associated with the design, procurement, and installation of the PV system. These are essential in ascertaining the viability of the project. For this project, the component costs are revised as follows:

1. Battery:
 - Type: Lithium-Ion (LG Chem RESU Prime 10)
 - Voltage: 51.8V
 - Capacity: 840Ah
 - Price per Battery: €2000
 - Number of Batteries: 4
 - Total Cost: €8000

Since lithium-ion batteries have higher energy density and efficiency to support up to 90% DoD, they will be selected for this purpose. In addition, their battery life will last longer with efficient operations.

2. PV Module:
 - Type: LG Chem 400 N2T-A5
 - Nominal Power: 400 Wp
 - Number of Modules: 8
 - price per module: €115
 - Total: €920

The LG Chem modules have been selected based on reliability and also compatibility with the system's design parameters in such a way that adequate energy is produced to meet the daily loads.

3. Charge Controller
 - Type: Generic MPPT 1000W
 - Capacity: 68A
 - Price: € 225

The MPPT charge controller provides maximum efficiency in energy transfer from the PV modules to the battery, minimizing energy losses.

4. Inverter:
 - Rating: 10 kW
 - Price: €1,375

A high-efficiency inverter provides consistent conversion of DC power into AC power, meeting the needs of the load appropriately.

5. Backup Generator:
 - Capacity: 3 kW (HVO-compatible for renewable fuel use)
 - Price: €900

It makes the system quite robust during periods of low solar availability by providing backup power to sustain it.

6. Installation and Labor Costs:

- Estimated Cost: €3,000 (no discount applied)
- Installation involves professional setting up, transportation, and labor charges required for the operation of the system as designed.
- Total Initial Cost: €13,520

4.6.1.2 Maintenance Costs

Maintenance costs: these are the costs of periodic monitoring, cleaning, and small repairs to keep the system running at its best for its lifetime. These have been summarized below:

- Annual Maintenance Cost: €500
- 20-Year Maintenance Cost: €10,000

4.6.1.3 Repair and Replacement Costs

Repair and replacement costs: these will be required for components that have a shorter life than the total life of the system. In this project:

- Battery Replacement (After 10 Years): €8,000 (batteries require replacement once within the 20-year system life).
- Charge Controller Replacement (After 10 Years): €225
- Total Replacement Cost: €8,225

4.6.1.4 Salvage Value

The salvage value is the residual value of the components of the system at the end of their life and can be estimated as 20% of the initial value of the movable components:

- Salvage Value: €2,704

Life-Cycle Cost Analysis

The life-cycle cost is a very important measure for determining the overall financial investment in the system during its 20-year life span. LCC can be determined as:

$$LCC = I + M_{PV} + R_{PV} - S_{PV} \quad (3.9)$$

Where:

- I = Initial Cost (€13,520)
- M_{PV} = Maintenance Cost (€10,000)
- R_{PV} = Repair and Replacement Cost (€8,225)
- S = Salvage Value (€2,704)

$$LCC = 13,520 + 10,000 + 8,225 - 4,484 = €29,041$$

3.4. Brief Description of design methodology

This is a carefully engineered and systematic design for the independent SPV system for the temporary construction near the Nakhchivan Solar Power Plant. The entire process is broadly undertaken in three broad steps: collection of data, detailed analysis, and modeling recommendations. Indeed, this has been an iterative process where the final design best fits the specific needs of the temporary structure, given the issues concerning maximum efficiency, durability, and overall performance.

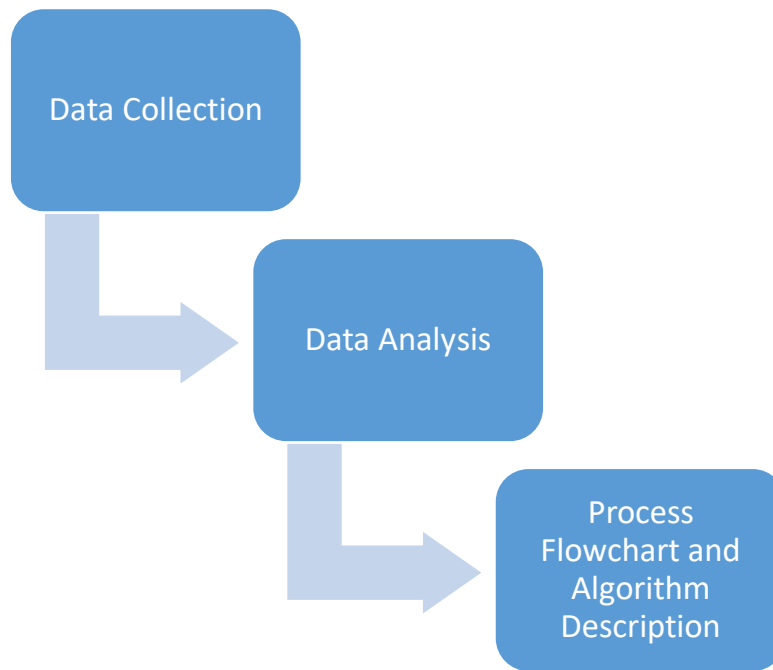


Figure 3.2: Design Procedure (Block diagram)

The given methodology for developing an effective and high-performance SPV system is sound and well-defined. It merges rigorous data collection with complex techniques of analysis and comprehensive simulation. Thus, it allows the final system design to utilize the solar potentials of the Nakhichevan region in meeting the specific energy needs of the temporary structure.

It also allows for detailed design and analysis of the standalone SPV system for the temporary structure near the Nakhchivan Solar Plant using rigorous data collection, detailed analysis, and system modeling using PVsyst. Thus, the study will ensure, during the design, that the system is energy-reliable, efficient, and sustainable during operation.

CHAPTER FOUR

RESULTS AND ANALYSIS

This chapter completely explains the PVsyst software and explains the methodology adopted in the design of an SPV system, both standalone and interfaced with the grid. This will have a focus on the temporary structure near the Nakhchivan Solar Power Plant. In addition, this chapter presents a scheme of the proposed system adapted to the potential of high solar radiation of the location chosen.

4.1 Overview of PVsyst Software

PVsyst is one of the comprehensive software tools that have general applications in the modelling, simulation, and analyses of various SPV systems, such as standalone systems, water pumping solutions, and grid-connected systems. PVsyst allows doing preliminary and detailed designing of systems by utilizing basic parameters like meteorological data and user-defined configurations.

The applications of PVsyst are as follows:

Standalone systems: It is used to design self-sufficient SPV systems for off-grid, temporary, or rural applications.

Grid-connected systems: SPV systems are designed to optimize the energy between SPV systems and grid networks.

Water Pumping Systems: It helps in the SPV design for agricultural and irrigation applications.

PVsyst utilizes meteorological data of latitude, longitude, azimuth, and other facts of a particular region for accurate system configuration. It allows the user to input parameters like module orientation, monthly or annual load consumption, and system characteristics such as rated power, battery capacity, and voltage. Based on the information, this tool estimates the power delivered, analyzes the energy production of the suggested system, and gives an idea about the cost of the same.

Main Features of Pvsyst:

System Configurations: Offers flexibility in the design of fixed plane and monitoring plane installations.

Component Datasets: Contains information about photovoltaic modules, batteries, inverters, charge controllers and interconn Decouples.

Loss Analysis: Simulates thermal, wiring, mismatch, contamination and incident angle losses.

Economic Evaluation: Provides cost analysis for components and system application.

Simulation Outputs: Displays changes in irradiation, energy output and battery performance over time.

For grid-connected systems, PVsyst is particularly effective in optimizing the orientation of solar panels, selecting system components, and evaluating system performance based on local environmental conditions. The software for standalone systems supports designing self-confident configurations that meet specific load requirements, while maintaining autonomy during periods of low solar energy availability.

4.2 Meteorological and Geographical data

PVsyst allows users to operate with two types of formats for meteorological data: monthly and hourly. In this work, the monthly meteorological data will be used, which is an efficient and very accurate basis for designing the standalone SPV system. The monthly data includes the following:

Horizontal Global Irradiation: Total solar energy received per square meter on a horizontal plane.

Diffuse Irradiation: The scattered radiation of sunlight.

Ambient Temperature: Averages of each month's temperatures.

Wind Velocity: Optional but useful for understanding cooling effects on the panels.

Unlike the hourly data, which requires additional detail, monthly data generation in Pvsyst is enough for system performance evaluation and optimization.

Location of Project: Temporary Structure Near Nakhchivan Solar Plant

The screenshot shows the 'Geographical Coordinates' tab in the Pvsyst software. The 'Location' section has a text input for 'Site name' containing 'Nakhchivan Solar Power Plant', a dropdown for 'Country' set to 'Azerbaijan', and a dropdown for 'Region' set to 'Asia'. There are buttons for 'Get from coordinates' and 'Show map'. The 'Geographical Coordinates' section features a 'Sun paths' button, input fields for 'Latitude' (39.3328) and 'Longitude' (45.4491) in decimal format, and corresponding fields for 'Deg. Min. Sec.' (39, 19, 58). It also includes an 'Altitude' field (1009 M above sea level) and a 'Time zone' field (4.0). A 'Get from name' button is at the bottom.

Figure 4.1. Geographical coordinates of Nakhchivan Solar Plant

Located very close to the Nakhchivan Solar Plant area, the project site falls within an area of very high solar potential that is highly suitable for SPV systems. Geographical and climatic conditions in the area are quite ideal for the applications of solar energy. The site coordinates will define the parameters in the Pvsyst simulations.

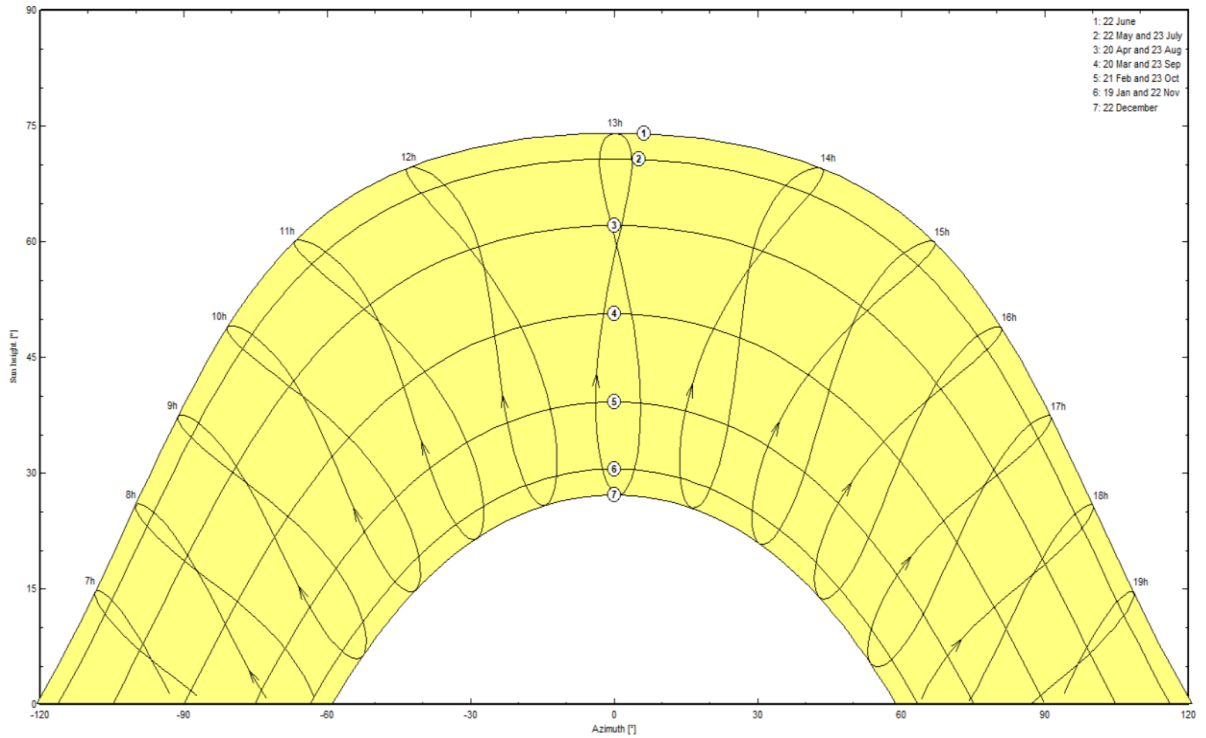


Figure 4.2. Sun Path of Nakhchivan Solar Plant

Monthly Data Integration for Simulation:

	Global horizontal irradiation kWh/m ² /mth	Horizontal diffuse irradiation kWh/m ² /mth	Temperature °C	Wind Velocity m/s	Linke turbidity [-]	Relative humidity %
January	76.6	21.3	-2.0	1.70	2.782	72.1
February	88.9	28.4	1.4	2.19	3.175	66.0
March	136.4	53.2	7.3	3.20	3.903	53.5
April	169.1	61.2	12.1	3.10	5.002	54.6
May	197.9	71.5	17.1	2.69	4.548	54.1
June	233.7	66.5	22.1	2.70	4.216	44.6
July	223.7	74.3	25.8	2.70	4.710	41.3
August	211.3	55.9	25.7	2.49	4.221	39.3
September	172.0	40.8	20.5	2.19	3.626	46.0
October	118.6	40.2	14.0	1.90	3.541	57.1
November	82.3	29.5	6.2	1.69	2.963	67.4
December	68.3	24.3	0.4	1.70	2.766	72.2
Year	1778.9	567.1	12.6	2.4	3.788	55.7

Figure 4.3. Monthly weather data

Meteorological data on a monthly basis serves as the prime input for this system design. The main steps used can be summarized as follows:

Location Definition: It defines the geographical coordinates of the Nakhchivan Solar Plant region, enabling precise analysis of the solar potential.

Month-wise Data: It includes horizontal global irradiation values and temperature during each month and forms the primary dataset. Inputs are very essential for evaluating the energy generation potential and system performance.

Optional parameters include diffuse irradiation and wind velocity, if available, and at places where data was not available due to lack of measurements, constant values were introduced.

The chosen approach of using monthly data saves computing, which is tedious and complex. At the same time, results are reliable, realistic, and accurate enough to be used confidently in standalone SPV systems for effective design.

The advantages of a monthly data-generating approach involve:

Approach Simplicity: Monthly data reduces computational complexity while maintaining the desired accuracy for any standalone SPV system design.

Seasonal Analysis: Monthly data entails season-specific values and thus keeps the system's fitting for top performance throughout the year.

Efficient System Integration: Allows accurate sizing of system parts composing photovoltaic panels, accumulators, and inverters.

This will surely ensure a strong and steady energy system because of the high solar irradiance at the Nakhchivan Solar Plant location. The processed monthly data from PVsyst presented system efficiency, energy output, and cost estimates that would guide the design and implementation of the Standalone SPV system for the temporary structure. Meteorological data on a monthly basis serves as the prime input for this system design. The main steps used can be summarized as follows:

Location Definition: It defines the geographical coordinates of the Nakhchivan Solar Plant region, enabling precise analysis of the solar potential.

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This approach is supposed to take advantage of monthly data generation and will take into consideration specific geographic and climatic features of the Nakhchivan region.

4.3. Orientation of PV modules.

The orientation of photovoltaic modules is paramount for optimum power generation in the entire solar energy system. It varies with the geographic location of the installation and takes variations through the year for the best performance. A simple rule of thumb is that the angle of tilt for the solar panel should be approximately equal to the latitude of the site. Although this is easy to use and inexpensive, this technique is an approximate one, and it does not provide maximum collection of energy.[20]

A fixed tilt is a very simple installation and service. Its efficiency is by far lower than the efficiency of other configurations, with the inability to change throughout the day and season with changes in the sun's positioning. An adjustable tilt mechanism can be used to increase energy captured. The design allows the setting of the tilt angle for manual adjustment to optimize aligning with the sun. For example, in summer, when the sun is high, the tilt angle is reduced, while in winter, it is increased to maximize the absorption of solar energy. Even with such adjustments, maximum power generation is still not achieved with adjustable tilt systems.

This challenge can, however, be addressed through sun-tracking systems that automatically change the angle of the panels to monitor the sun's position throughout the day. Sun tracking systems keep photovoltaic panels oriented with their surface at right angles to the sun's rays throughout the day for maximum input of energy. Systems enabled with sun trackers can result in up to 40% more power compared with fixed-mount systems.

Sun tracking systems can be classified according to the number of axes and type of rotation, like:

1. Single-axis tracking-it rotates the array around one axis, either vertical for changing the azimuth or horizontal, east-west-also integrates simultaneous adjustments of the tilt angle.
2. Two-axis tracking-this is a configuration whereby, along two axes, independent adjustment is possible; it will then, in such a way, be capable of orienting itself with much precision towards both the angles of azimuth and altitude.

The common configurations include the following:

Altitude - Azimuth tracking: one axis modifies the angle of azimuth, while another one modifies the tilt angle, depending on the sun altitude variation.

Equatorial tracking: N-S axis for east - west rotation, to which is added a periodic tilt axis during the year.

It provides a range of orientations of the photovoltaic modules within the PVsyst software: fixed tilt, tracking system, or even an adjustable tilt of photovoltaic modules. With this option, there opens up large prospects for optimization of system performance depending on specific site conditions and energy demands.

The possible orientation configurations of the photovoltaic modules impact greatly on optimizing power generation in the solar system. Thus, for a temporary structure located near the Nakhchivan Solar Plant, several orientation schemes are available in PVsyst, each having different benefits depending on the requirements of application. Available configurations are as follows:

a. Fixed Tilted Plane: This is the simplest one where the user has only to set the tilt angle and the azimuth angle. This is cost-effective and easy to install.

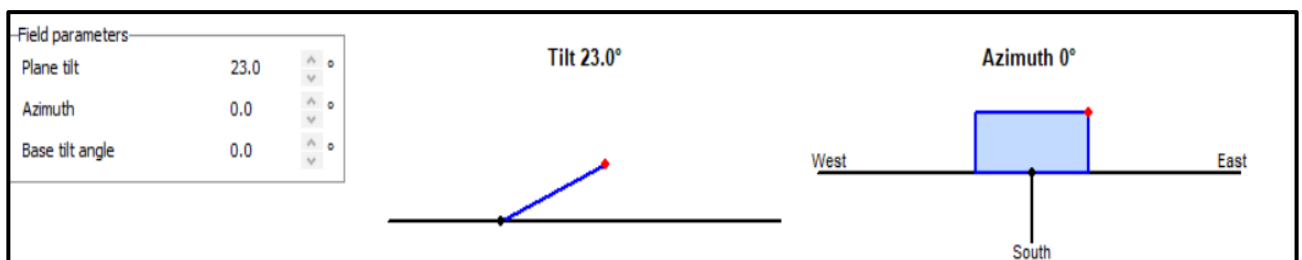


Fig 4.4: Fixed Mount Array

b. Adjustment of the tilt seasonally: It means changing the inclination of the photovoltaic panels concerning the seasons. A general example would be lower tilt during summer and higher during winter, for more or better absorption of solar energy throughout the year.

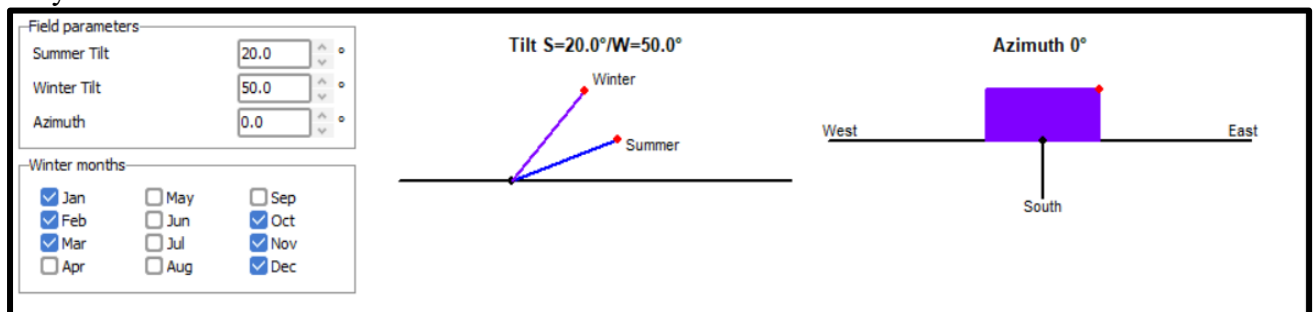


Fig 4.5: Adjustable Tilt Mounting

c. One-Axis Tracking (Vertical Axis): Solar panels are mounted on a vertical axis, but the whole panel will rotate to orient itself with the sun's path. It increases energy output due to a better orientation of the sun during the day.

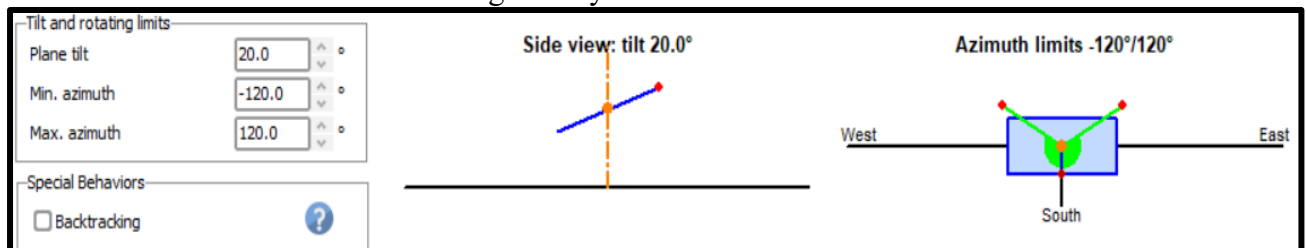


Fig 4.6: Vertical Axis Tracking

d. One-Axis Tracking (Horizontal Axis E-W): This configuration is such that the axis of orientation is perpendicular to the horizontal plane. Although not ideal for photovoltaic systems, this may be applicable for some applications. There shall be stroke limits provided that would limit the movement of the panels.

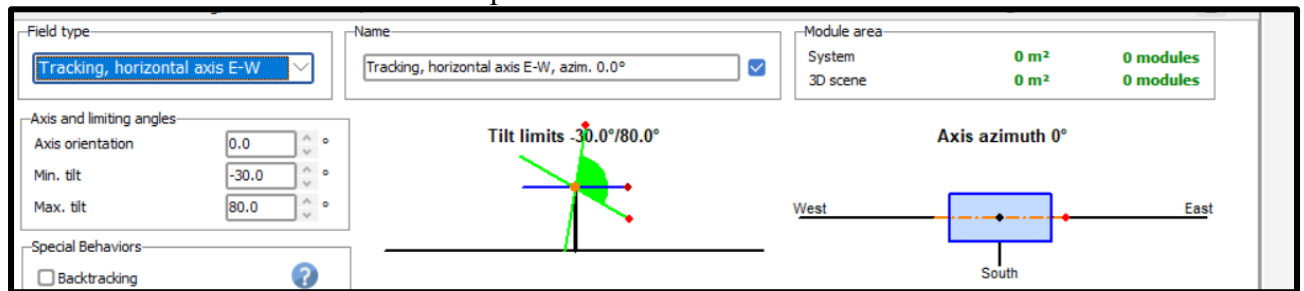


Fig 4.7: Horizontal Axis Tracking

e. Two-Axis Tracking (Tilted Axis): In this system, both the tilt and azimuth angles are adjustable. It enables better tracking of the sun's position, improving energy capture efficiency.

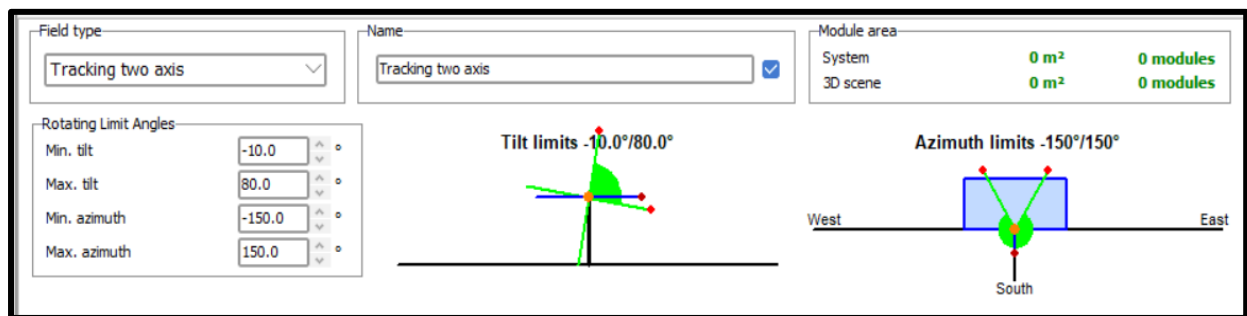


Fig 4.8: Two-Axis Tracking Mounting

f. Two-Axis Tracking (Horizontal Axis N-S): This configuration uses a horizontal north-south axis to rotate the array from east to west. It is a commonly used setting for tracking systems, where the tilt angle remains fixed at 0 degrees.

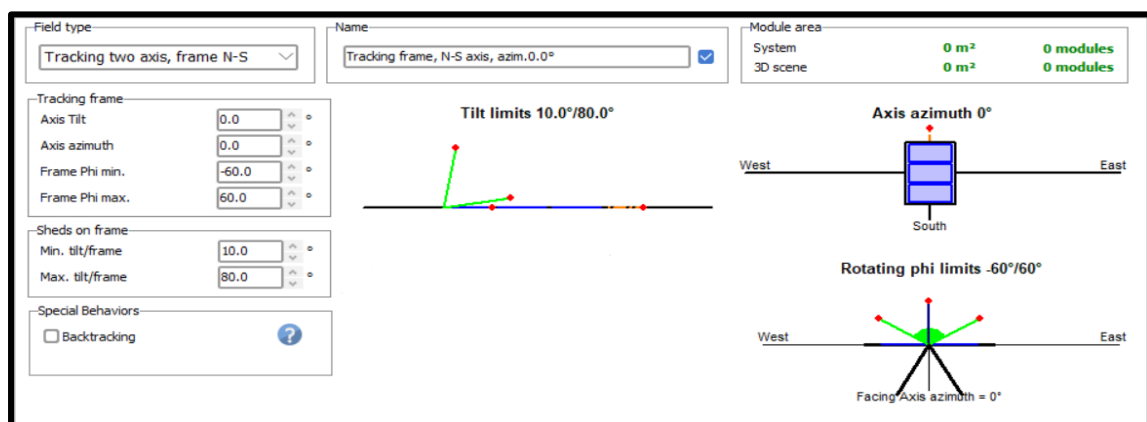


Fig 4.9: Two-Axis Horizontal Axis N-S

To put it more precisely, with regards to the Nakhchivan Solar Plant location, due to economic feasibility and requirements for maintenance, a fixed tilt angle option is chosen as a simulation model. Normally, the optimum tilt is going to be the latitude of the place. From the coordinates of the Nakhchivan location, change the tilt angle accordingly. Using the plane optimization tool in PVsyst, users will get the tilted and azimuth angles of the system. Since the latitude of Nakhchivan is 25.4 degrees,

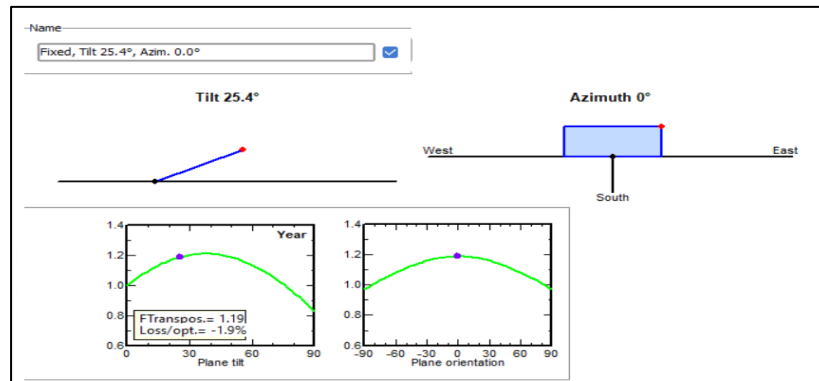


Fig 4.10: Orientation of Panel Used in the PV System

These configurations provide flexibility in design and allow for the customization of solar panel orientation to maximize energy output for the specific needs of the project.

4.4 Stand-alone system sizing

4.4.1 Load Analysis

The determination of the energy consumption pattern is a very important stage in the design of the standalone system, which will be installed for the temporary structure at the Nakhchivan Solar Plant. The estimation of energy consumption in such systems is usually done daily, monthly, or yearly. The daily energy demand of each load will be forecasted with respect to its power rating and operating time. Accurate estimation of loads is required for proper sizing of the system and designing major components like batteries and inverters.

In the case of AC loads, it requires an inverter that would convert the DC power generated by the PV array or stored in the batteries to AC voltage. The rating of the inverter selected is based on the connected loads' peak power requirement. Normally, the inverter rating is chosen to be somewhat higher than the calculated load to allow for efficiency losses and perhaps potential future expansions. In general, inverters operate in the range of 80 to 95% efficiency.

4.4.1.1 Assumptions

The standalone system is designed for a site located near the Nakhchivan Solar Plant. The load requirements for the temporary structure are estimated based on assumed usage patterns and operational hours. The main connected loads are lighting, appliances, and media devices. To simplify the calculations, these loads are treated as being in a steady state for each month. The energy consumption of each device is calculated by multiplying its power rating by its average daily operating time.

Example:

- Lighting: LED lamps rated at 15W, each used for 6 hours per day.
- Fans: Standard ceiling fans rated at 50W, each operating for 8 hours daily.

-Audio Video: A television rated at 120W used for 3 hours a day, and a computer rated at 200W used for 2 hours a day.

This includes the additional load due to air conditioners in summer, which can be analyzed from the following table regarding energy consumption in the summer season. That would provide full insight into the system performance requirements during peak periods.

Table 4.1: AC Load analysis for the month of summer

Load	Number	Power rating(W)	Operating time (h/day)	Energy Consumption (Wh/day)
LED Lamp	4	15	6	360
Ceiling Fan	3	50	8	1200
Refrigerator	1	150	10	1500
Dishwasher Machine	1	500	0.5	250
Television	1	120	3	360
Computer	1	200	2	400
Air Conditioner	1	1000	4	4000

Total AC Energy Consumption (Summer): 8070 Wh/day

Inverter Efficiency (90%):

Average DC Energy Consumption = $8070/0.9=8967$ Wh/day

Therefore, in summer, the inverter needs to provide at least 8.1 kW of power. For contingency and allowing for possible future load increase, an inverter capacity of 9 kW is recommended.

Seasonal Variations and Critical Design Month

The system must be able to accommodate seasonal load variations and changes in solar irradiance. The critical design month is identified as the month with the highest ratio of energy consumption to available solar energy (peak sun hours). This ensures that the system performs reliably even during periods of low solar irradiance.

The PSH for the Nakhchivan region is as follows: PSH refers to the number of hours per day with solar irradiance of 1000 W/m². Seasonal PSH data is used to calculate the critical design ratio as expressed below:

Critical Design Ratio = Daily DC Energy Consumption (Wh)/PSH (kWh/m²/day)

The load is seasonally adjusted as expressed below:

Summer (May–August): Includes air conditioning and fans; estimated daily DC energy is 8967 Wh.

Winter (November–February): Without air conditioning, this maintains the load for lights, refrigerator, and media equipment; the daily DC energy is 4587 Wh.

Rainy Season (September–October): Same as winter loads, daily DC energy is approximately 4587 Wh.

Using the monthly critical design ratio, the critical design month of the system is determined to be February because the solar irradiance is very low, and the load is high.

Then it is possible to calculate the critical design ratio for each month:

Table 4.2: Critical Design Ratio Analysis for Nakhchivan Solar Plant Location

Month	Season	Daily DC Energy Consumption (Wh)	Final Load Needs (Wh/day)	Insolation (PSH/day)	Critical Design Ratio
January	Winter	4587	5097	5.455	934.21
February	Winter	4587	5097	6.081	838.15
March	Winter	4587	5097	6.562	776.71
April	Winter	4587	5097	6.694	761.34
May	Summer	8967	9963	6.265	1590.30
June	Summer	8967	9963	4.492	2218.35
July	Summer	8967	9963	4.211	2365.95
August	Summer	8967	9963	4.383	2272.23
September	Rainy Season	4587	5097	5.010	1017.21
October	Rainy Season	4587	5097	5.483	929.28
November	Winter	4587	5097	5.303	961.17
December	Winter	4587	5097	5.228	974.58

This will be supported by the insolation data from the TMY3 dataset, which will give values of monthly and daily global irradiance. Employing these data, a critical design ratio is then calculated month by month. The critical design ratio refers to energy consumption divided by insolation for the month to be sure that the system can meet the highest demand in the month when the sunlight conditions are the poorest.

Daily consumptions							
Number	Appliance	Power		Daily use	Hourly distrib.	Daily energy	
4	Lamps (LED)	15	W/lamp	6.0	h/day	OK	360 Wh
3	Ceiling fan	50	W/app	8.0	h/day	OK	1200 Wh
1	Washing machine	500	W/app	0.5	h/day	OK	250 Wh
1	Fridge	0.15	kWh/day	10.0		OK	150 Wh
2	TV	120.0	W aver.	3.0	h/day	OK	720 Wh
1	Computer	200	W/app	2.0	h/day	OK	400 Wh
1	AC	1000	W/app	4.0	h/day	OK	4000 Wh
Stand-by consumers		90	W tot	24	h/day		2160 Wh
						Total daily energy	9240 Wh/day
						Monthly energy	277.2 kWh/mth

Fig 4.11. Used load analysis in PVsyst.

4.4.2. Array and Battery sizing

4.4.2.1. Battery pre-sizing parameters

Requested autonomy is the number of days that the battery can support the load without input from solar power. In this design, lithium-ion batteries are preferred due to their high DOD and longer life span compared to lead-acid batteries. System autonomy is set at 4 days as a balance between cost, maintenance, and operational reliability. A larger autonomy period increases the size and cost of the battery bank but minimizes depth of discharge, hence prolonging battery life.

Probability of Loss of Load (LOLP): The LOLP calculates the percentage of time in a year that the load demand cannot be satisfied by the PV system due to lack of insolation or losses in the system. In this project, it is taken as 5%, which is the standard for stand-alone systems. The factors that influence LOLP are the autonomy, battery capacity, and availability of insolation.

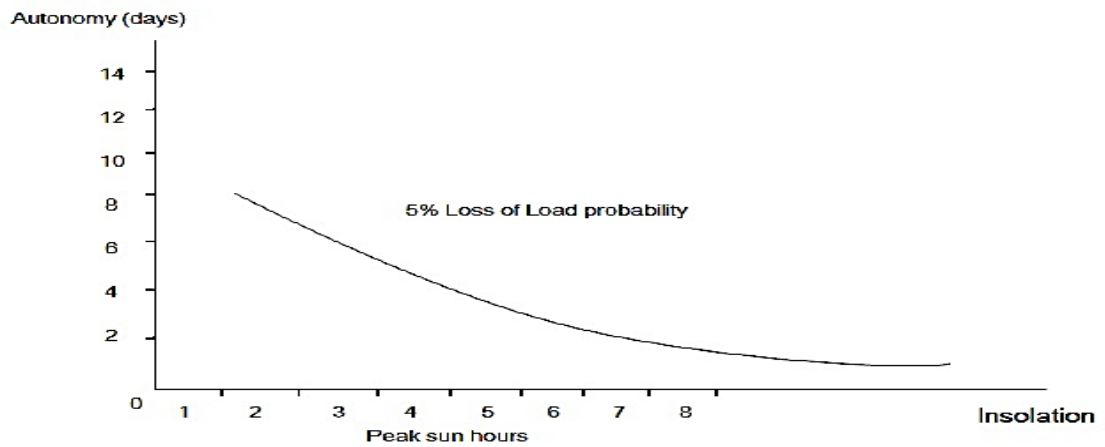


Fig 4.12: Factors influencing LOLP, such as Insolation and Autonomy.

Battery Voltage

A lithium-ion battery with a nominal system voltage of 51.8V selected and matched with the demand load. A higher voltage can reduce current, which may decrease power loss, improving the overall efficiency by reducing the size of components like charge controllers and inverters that support it.

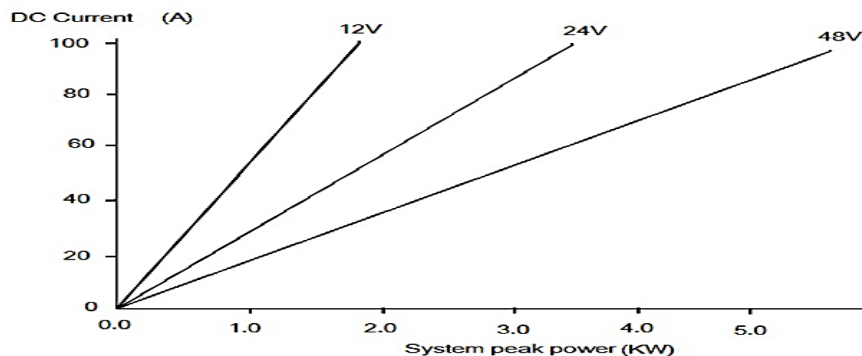


Fig 4.13: System Voltage vs. Current (DC).

4.4.2.2. Battery sizing

In real applications, the size of the battery must account for DOD, temperature, and discharge rate. Most lithium-ion batteries are designed to work within 80-90% DOD, which would reduce over-sizing. The final sizing of the battery, including the aforementioned considerations, is as follows:

- Manufacturer: LG Chem
- Model: RESU Prime 10 (high-efficiency lithium-ion)
- Voltage: 51.8V
- Nominal Capacity: 840 Ah
- Number of Batteries in Series: 1
- Number of Strings in Parallel: 4

To ensure practical use and account for efficiency losses, the battery capacity must accommodate factors such as:

Temperature Effect: The capacity of a battery decreases with lower temperatures. A temperature compensation chart or a factor to adjust capacity for deviations from the standard test conditions (25°C) is normally provided by the manufacturers.

Discharge Rate: The effective capacity of a battery decreases with high discharge rates. Lithium-ion batteries have a better performance when it comes to high discharge rates compared to other chemistries.

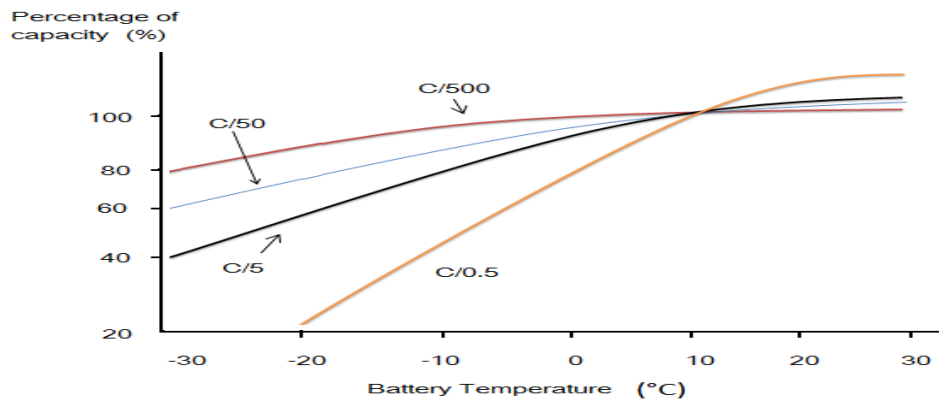


Fig 4.14. Effect of temperature on battery capacity.

The **selected battery** for this project is the LG Chem RESU Prime 10, a lithium-ion battery known for its high energy density and efficiency.

Table 4.3. Selected Battery Specifications.

Parameter	Value
Manufacturer	LG Chem
Model	RESU Prime 10
Nominal Voltage	51.8 V
Nominal Capacity	840 Ah
Energy Capacity	43.5 kWh
Depth of Discharge (DOD)	90%
Efficiency	95%

In PVsyst, several batteries from different manufacturers can be chosen, having their datasheet with detailed specification. The datasheet shows a number of important parameters like DC voltage, capacity, and efficiency. A 51.8V lithium-ion battery manufactured by LG Chem was chosen based on its capacity and suitability for the system voltage and autonomy. Among these, selected is the LG Chem RESU Prime 10, with a nominal voltage of 51.8V and an 840Ah capacity, proving to be highly efficient with the capability of meeting the required energy demand as specified by the design.

Specify the Battery set

Sort batteries by: voltage capacity manufacturer

LG Chem | 51.8 V | 193 Ah | Li NMC | RESU 10 | 8.8 kWh | Since 2018 |

Lithium-ion | The selected battery is a module

1 modules in series | Number of modules: 4

4 modules in parallel | Number of elements: 168

100.0 % Initial State of Wear (nb. of cycles)

100.0 % Initial State of Wear (static)

Battery pack voltage	52 V
Global capacity	779 Ah
Stored energy (80% DOD)	36.0 kWh
Total weight	300 kg
Nb. cycles at 80% DOD	6250
Total stored energy during the battery life	204 MWh

Fig.4.15. Specifications of used battery

4.4.2.3 PV array sizing

Proper sizing of the PV array is important to ensure adequacy in the energy supply for the loads and to maintain an adequate charge in the batteries. The required array output current is calculated first from the daily energy consumption and DC system voltage. However, the actual array output current will have to be higher than this theoretical calculation, while considering that battery charging efficiency, which commonly lies in the range of 85% to 95%, is hardly ever 100%.

This means that the PV array should be able to provide at least 35.89 A of current to keep the loads functioning properly under peak sun hour conditions. However, just like the battery capacity, the actual array output is affected by several factors that prevent it from achieving the theoretical maximum. Among these factors, soiling and temperature are the most prominent. This will surely increase the size of the array due to these influences to capture the desired array output.

Soiling represents the deposition of dust and dirt on the surface of the PV array that may create shading and further reduce solar insolation. Normally, the soiling factor coefficient is 0.95 for light soiling conditions and 0.9 for heavier soiling.

Another factor affecting the PV array performance is temperature. It affects the voltage output. More specifically, for every degree over 25°C, the voltage decreases by 0.45%. Also, since the charging voltage is higher than the operational voltage needed, the required voltage needs to be multiplied by 1.2 to account for the charging voltage. PV Module Selection and Configuration

It, therefore, involves the choice of an appropriate module and how many will be connected both in series and parallel strings, based on the computed rated voltage and current needs of the system.

In this project, the selected module is LG 400 N2T-A5, whose specifications are as follows:

- Nominal Power: 400 Wp
- Open Circuit Voltage (Voc): 49.30 V
- Maximum Power Voltage (Vmp): 41.6 V
- Short Circuit Current (Isc): 10.12 A
- Maximum Power Current (Imp): 9.61 A

Using these specifications, the array configuration is determined as follows:

Modules in Series: To meet the rated voltage (67.19 V):

Modules in Series= $67.19/41.6 \approx 2$

Therefore, 2 modules are connected in series.

Strings in Parallel: To satisfy the rated current (39.88A):

Strings in Parallel= $39.88/9.61 \approx 4$

So 4 strings are paralleled.

Table 4.4. Summary of Array sizing parameters

Parameter	Value
Average daily DC energy consumption	9240 Wh/day
DC system voltage	51.8 V
Critical design month insolation	5.75 PSH/day
Battery charging efficiency	90%
Required array output current	35.89 A
Soiling factor	0.9
Rated array output current	39.88 A
Temperature coefficient for voltage	0.45%/°C
Maximum operating temperature	50°C
Reference operating temperature	25°C
Rated array operating voltage	67.19 V

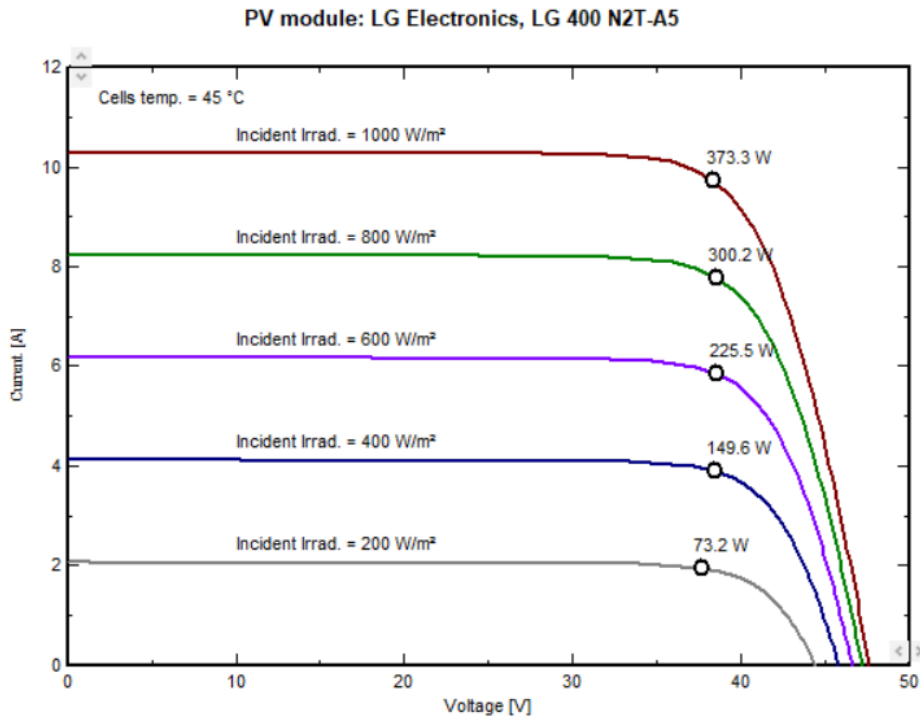


Figure 4.16. I/V characteristics given under irradiance of 1000W/m2

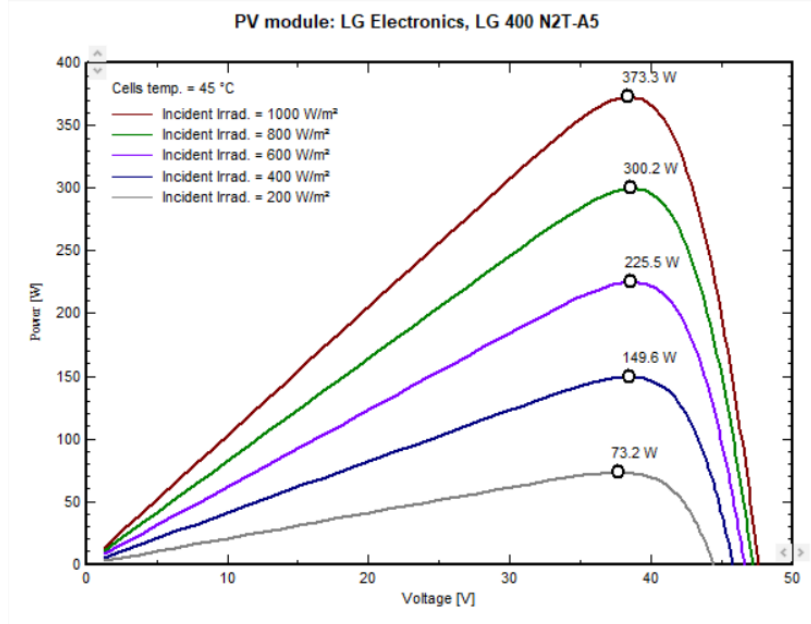


Fig 4.17. P /V characteristics given under irradiance of 1000W/m2

Conclusively, the irradiance and module temperature are the main factors affecting the output power of a photovoltaic system. Utilizing PVsyst will be effective in analyzing and demonstrating how the performance of the module would behave under different irradiance and temperature conditions.

4.4.3 Charge Controllers

A very critical step in the design of the standalone PV system is the selection of a charge controller. A controller, often called the regulator, operates in controlling power flow from the PV array to the battery bank and to the load. It ensures optimum charging of the batteries to avoid overcharging or deeply discharging them, thus increasing efficiency in the system.

In PVsyst, the charge controller has all functions integrated into one package: inverter, rectifiers, transformers, and DC-DC converters, hence can manage the power fully. The maximum power point tracker is chosen for this project because it continuously optimizes the power extracted from the PV array by changing the operating point.

Main Settings Parameters of Charge Controller:

Voltage Regulation Set Point: It sets the maximum voltage level at which the battery will be charged to avoid overcharging.

Array Reconnect Voltage: It makes sure that the array reconnects to the battery system once the voltage falls below a set threshold.

Low Voltage Disconnect (LVD): It protects the battery against low voltage by disconnecting the loads once the voltage drops below a critical level.

Load Reconnect Voltage: Reconnects the load once the battery voltage improves to a safe operating range.

Where necessary, PVsyst would assume the values of such parameters on the basis of both battery type and system configuration; however, it also requires further optimization based on particular applications. Additionally, these depend on the battery type based on maximum DOD of the battery and system types.

Selected Charge Controller for the System:

The choice is Generic Universal Controller MPPT converter.

Table 4.5. Details of Charge Controller

<i>Parameter</i>	<i>Value</i>
Description	Generic, Universal controller with MPPT converter
Minimum MPP Voltage	50 V
Maximum MPP Voltage	90 V
Maximum Array Voltage	116 V
Power Threshold	27.8 W
Nominal Output Power	2.56 kW
Maximum Output Power	2.78 kW
Nominal Output Voltage	52.0 V
Nominal Output Current	49.2 A

Compatibility of the System Voltage: The controller has compatibility with the 48V system voltage that this application calls for.

High Charging Capacity: It can charge at 68 amps and would be sufficient to supply the current generated from the PV array and distribute it into the battery bank.

MPPT Efficiency: This controller ensures maximum power extraction from the PV array at different irradiances and temperatures.

Adaptability: Universal compatibility makes this bank suitable for integration with numerous battery technologies, including Li-ion batteries adopted in this project.

Recommended Selection Guidelines of Charge Controller:

Compatibility: The appropriate match of a charge controller needs to be selected according to system voltage and must support total current generated by the PV array.

MPPT prevalence due to higher efficiency and energy throughput, especially in systems subjected to fast and abrupt changes in solar conditions.

Sufficient current rating: the controller must be rated to handle more current than the maximum current produced by the PV array to handle safely peak conditions.

Matching the controller with the battery type, lithium-ion technology for better charging cycles and long life.

Advanced Functions: Consider controllers that provide advanced monitoring and data logging functions to further enhance the performance analysis of the system.

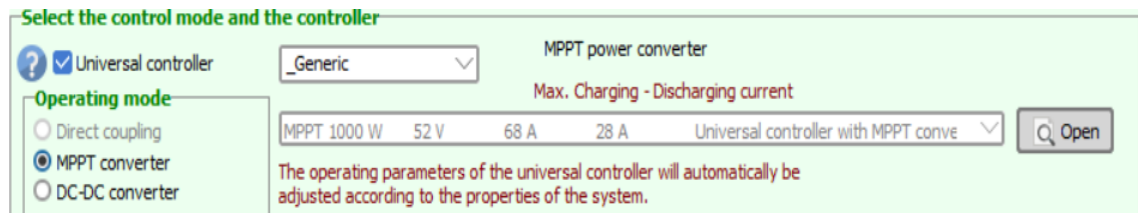


Figure.4.18. Charge controller specifications

4.4.4 Standalone System Layout for Rural Domestic Use

The standalone PV system is designed to supply power to a rural residence near Nakhchivan. In the design, the monthly load evaluation is considered to ensure that the demand of the system is met throughout the year. The components selected for this purpose are PV modules, lithium-ion batteries, an MPPT charge controller, and an inverter, which are optimized for efficiency and reliability.

To improve system reliability for periods of prolonged low insolation or unforeseen high energy demands, a 3-kW backup generator running on Hydrotreated Vegetable Oil (HVO)-biofuel is included in the stand-alone PV system. This ensures a renewable energy-efficient solution while maintaining an uninterrupted power supply.

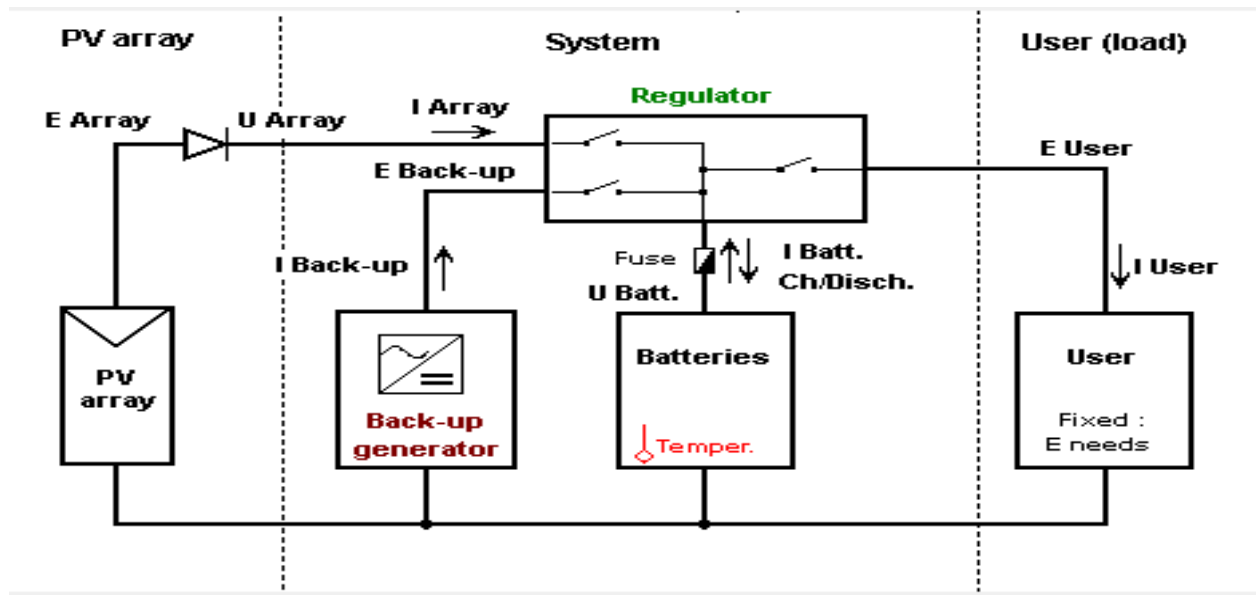


Figure 4.19. Typical layout of Stand-alone system.

Overview of System Diagram:

PV Array: Four strings of LG Chem 400 Wp modules connected to the charge controller.

Battery Bank: Two lithium-ion batteries RESU Prime 10 are paralleled for the meeting autonomy and capacity requirements of the system.

Charge Controller: Generic MPPT controller manages energy inflow into the battery bank toward the inverter.

Inverter: Provides AC power supply to the household appliances.

Backup Generator: Engages when battery levels fall below a critical threshold, maintaining continuous power. The HVO-fueled generator supports the system by:

1. **Battery Charging:** Recharges the battery bank when PV generation is insufficient.
2. **Load Support:** Directly powers critical loads during peak demand or extended low-insolation days.
3. **Renewable Efficiency:** Low reliance on fossil fuel, as HVO is a low-carbon, sustainable biofuel.

Load Distribution: Supplies power to lighting, refrigeration, and media equipment with a daily demand of 9240 Wh.

4.5 Grid-Connected System Design

The design of a grid-connected PV system is somewhat easier than that of a stand-alone system because the external utility grid is used. If the energy generated by the PV array is in excess of what is required, the surplus is fed into the utility grid, while if the PV system cannot meet the demand placed on it, the utility supplies the additional electricity. A battery bank is therefore not required in a grid-connected system.

For consistency in design and economic analysis, the grid-connected system is chosen for a domestic application to be installed at Nakhchivan, with similar modules and loads to those used for the standalone system. The critical design concept is not employed because battery backup is excluded in grid-connected systems; the aim will be for the system to meet the requirements of average energy. Energy consumption for the month of April is used for

design, representing an average AC load of 9,240 Wh/day or approximately 277.2 kWh/month.

4.5.1 Insolation

The average insolation data for the Nakhichevan Solar Plant is derived from local meteorological records. The yearly average insolation is 5.42 PSH (Peak Sun Hours), meaning the daily solar irradiance of 1000 W/m² is available for an average of 5.42 hours per day.

Summary of Grid-Connected System Design

The grid-connected system consists of six LG 400N2T-A5 modules to produce the required energy. Since there is no battery bank, the system layout is straightforward, and excess energy is fed into the utility grid for efficient energy management.

This design will not only cater to the energy demand but also provide a framework for scalability in further expansion, keeping a high percentage of renewable energy.

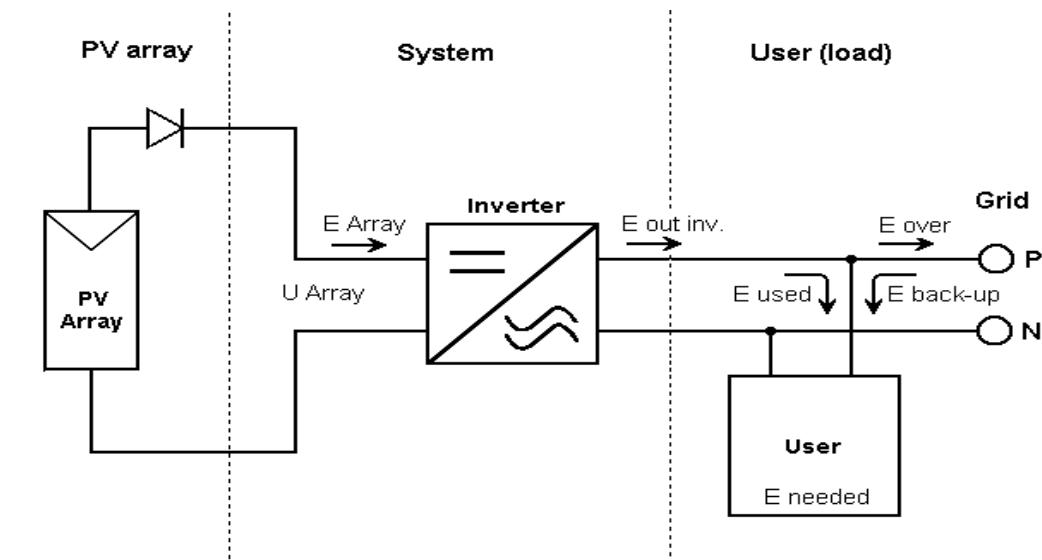


Figure 4.20. Typical layout of Grid-connected system

4.6. Economic Analysis with Detailed Information and Results

Economic analysis is a very important step in assessing the viability of the photovoltaic systems designed, both for stand-alone and grid-connected designs. This analysis will provide a thorough view of the financial aspect of the designed system with realistic figures by applying a 50% discount on the cost of components and focusing on the life-cycle cost (LCC).

Results and Discussion

Stand-Alone PV System:

The life-cycle cost of the stand-alone PV system with components is €29,041 for 20 years. This design allows complete energy independence, and, therefore, it is very suitable for remote or off-grid locations. The addition of a backup generator with HVO fuel increases the reliability of the overall system during periods of low solar radiation for several days.

A grid-connected PV system does not require batteries and therefore costs a lot less at about €20,000 for the same period. It requires grid connectivity and therefore cannot be used in areas where connectivity is poor or unavailable.

Comparison and Insights

While the grid-connected system is more cost-effective, the stand-alone system's independence and sustainability make it a superior choice for areas without grid access. Additionally, the use of HVO fuel for the generator aligns with renewable energy goals, further reducing carbon emissions.

Conclusion

The updated economic analysis shows the financial viability of the stand-alone PV system with component costs. Although the LCC is higher than in grid-connected systems, this design offers long-term benefits that include energy independence and reduced environmental impact, hence making it a sustainable solution for rural and remote applications.

4.7. Simulation Using PVsyst

4.7.1. Simulation Process

When the system configuration is finished and all the project parameters are set, simulations can be run by PVsyst in different ways. These simulations are realized from the meteorological data specified in the project and are usually restricted to a user-defined period. The result of the simulation consists of the calculation, by PVsyst, of about 50 variables, classified according to their nature. The results may be output as monthly, daily, or hourly data, although not all variables are available at the hourly time step. At the beginning of the simulation, a user can specify which variables to write out at hourly frequency or define graphical curves by assigning variables to both the X and Y axes.

The irradiance calculation is the start of the whole simulation process, such as effective global irradiance and array virtual energy at the MPP. On the other side, simultaneous calculation of variables that weight in the result is processed: diffuse and albedo attenuations for irradiance and array temperature for energy at MPP.

These steps apply to all system types. In standalone systems, PVsyst simulates array energy production, battery behavior, and user energy consumption concurrently. The system calculates current as a function of voltage for each component, as detailed below:

PV Array: Current calculations consider the module's I-V curve, Ohmic losses, module quality, and mismatch losses.

Battery: Voltage is a function of SOC, temperature, and current; current is determined based on energy consumption by the loads as a function of voltage.

For every time interval, it updates the SOC and voltage of the battery. The strategy adopted by the charge controller also acts as another key factor to the overall performance of the system, being responsible for the energy exchange between the battery and the load.

In the case of a grid-connected system, the simulation takes into consideration the inverter's behavior at different conditions:

1. If the maximum power output of the array falls below the threshold level of the inverter, then the array operates in an open-circuit state.
2. If the output from the inverter goes beyond its nominal power, then it limits the current or reduces input power as specified.
3. At the boundary point, the system operates when the MPP voltage reaches the inverter's operational limits.
4. Under normal conditions, the array operates at MPP, and inverter input energy is calculated based on its efficiency curve.

In every scenario, the losses are computed separately, while the energy consumption for the defined loads is estimated. PVsyst will perform very detailed calculations of the critical variables, including PV array performance, inverter operation, energy output, and energy usage for both standalone and grid-connected systems.

4.7.2. Results

PVsyst gives the results of the simulation as detailed reports. These reports include KPIs and variables for which the monthly, daily, or hourly values are available, depending upon the user requirement. Specific results for the stand-alone systems are given below.

4.7.2.1 Stand-Alone System Results

The simulation of the stand-alone system focuses on battery characteristics, array output, and energy usage. The objective of this simulation is to confirm the system design described in Chapter 3. Highlights of the results are presented by:

- Main Results: The main output of the simulation consists of the trends of battery SOC, daily energy consumption, and energy production by the PV array.

Balances and main results								
	GlobHor kWh/m ²	GlobEff kWh/m ²	E_Avail kWh	EUnused kWh	E_BkUp kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	76.6	114.8	358.1	59.2	0.00	286.4	286.4	1.000
February	88.8	117.3	358.1	82.3	0.00	258.7	258.7	1.000
March	136.3	160.8	473.9	176.0	0.00	286.4	286.4	1.000
April	169.1	179.5	515.3	227.0	0.00	277.2	277.2	1.000
May	198.1	193.9	546.3	249.0	0.00	286.4	286.4	1.000
June	233.5	222.9	608.6	319.9	0.00	277.2	277.2	1.000
July	223.6	218.0	586.9	288.8	0.00	286.4	286.4	1.000
August	211.3	220.4	592.0	294.0	0.00	286.4	286.4	1.000
September	172.0	196.2	539.1	250.8	0.00	277.2	277.2	1.000
October	118.5	153.0	439.2	143.0	0.00	286.4	286.4	1.000
November	82.3	119.3	358.4	79.9	0.00	277.2	277.2	1.000
December	68.4	105.0	325.3	31.2	0.00	286.4	286.4	1.000
Year	1778.4	2001.1	5701.3	2201.1	0.00	3372.6	3372.6	1.000

Legends			
GlobHor	Global horizontal irradiation	E_User	Energy supplied to the user
GlobEff	Effective Global, corr. for IAM and shadings	E_Load	Energy need of the user (Load)
E_Avail	Available Solar Energy	SolFrac	Solar fraction (EUsed / ELoad)
EUnused	Unused energy (battery full)		
E_Miss	Missing energy		

Fig 4.21. Main Results

- System Losses: The simulation indicates the losses caused by thermal effects, wiring resistance, module mismatch, and soiling.

	ModQual	MisLoss	OhmLoss	EArrMPP	EArUfix	EUnused	EArray
	kWh	kWh	kWh	kWh	kWh	kWh	kWh
January	4.340	3.135	6.757	275.1	275.1	9.51	265.6
February	4.140	2.991	6.781	262.1	262.1	32.25	229.8
March	4.609	3.329	7.737	291.6	291.6	36.00	255.6
April	4.304	3.109	6.797	272.7	272.8	25.29	247.4
May	4.232	3.057	6.510	268.3	268.3	18.33	250.0
June	3.178	2.296	4.266	202.2	202.2	0.00	202.2
July	3.107	2.244	3.997	197.8	197.8	0.02	197.8
August	3.300	2.384	4.328	210.0	210.0	0.05	209.9
September	3.463	2.502	4.758	220.2	220.2	0.01	220.2
October	3.936	2.843	5.862	249.8	249.8	0.00	249.8
November	3.959	2.860	6.310	250.8	250.8	2.47	248.4
December	4.263	3.079	6.515	270.3	270.3	16.64	253.7
Year	46.832	33.828	70.618	2970.9	2971.2	140.58	2830.3

Fig 4.22. Loss Diagram of PV System

- Performance Ratio: The performance ratio PR shows the overall efficiency of the system. It is calculated as a ratio between actual energy delivered and the expected output under standard test conditions.

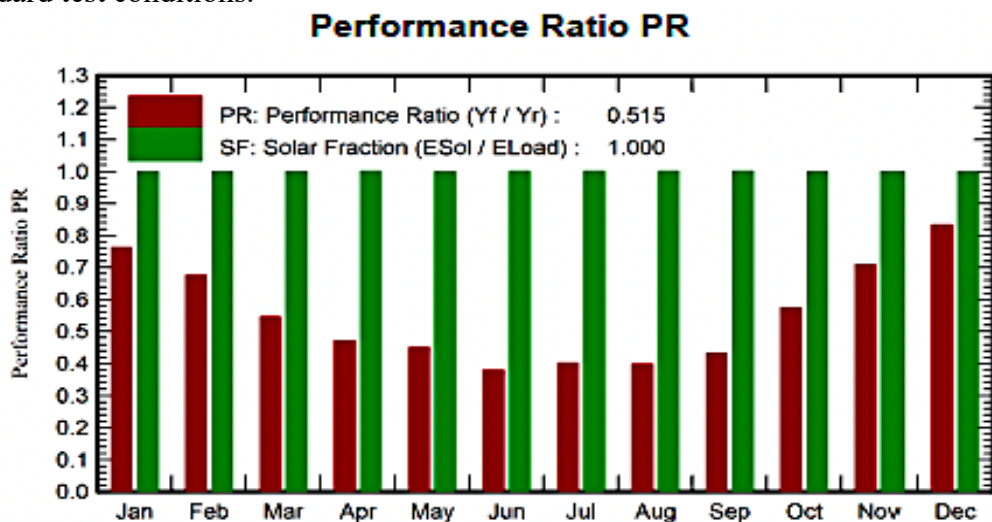


Fig 4.23. Performance Ratio (Stand-alone)

- Loss Diagram: In the urban application, the losses are accounted for and the modification in the system design is presented for better efficiency.

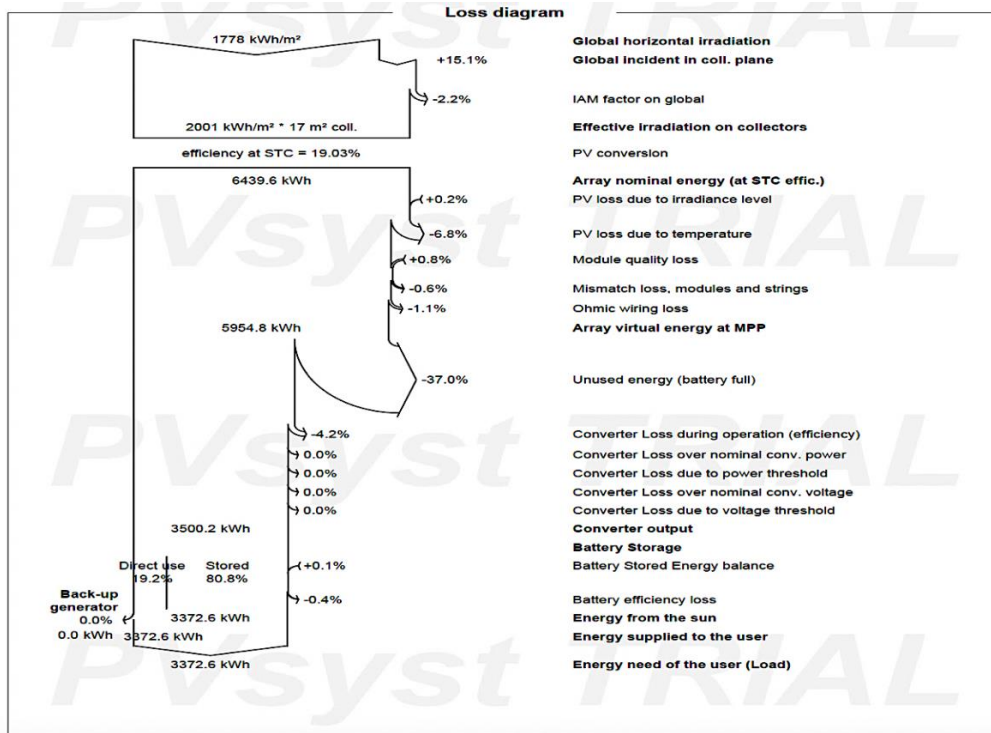


Fig 4.24. Loss Diagram for Stand-alone System

4.7.2.2. Grid-connected system results.

The array output and energy usage mainly concentrated in system performance while simulating a grid connected system. In chapter 3, the grid-connected system is described. Figure shows the PV Characteristics.

Balances and main results								
	GlobHor	DiffHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m ²	kWh/m ²	°C	kWh/m ²	kWh/m ²	kWh	kWh	
January	160.5	47.80	23.33	189.4	184.5	275.9	259.2	0.782
February	164.8	47.80	25.65	185.1	180.2	264.3	248.3	0.767
March	199.5	56.10	28.05	210.0	204.2	295.1	277.2	0.754
April	196.4	78.00	28.58	194.1	188.0	275.1	258.5	0.761
May	201.3	74.10	28.13	189.1	183.2	270.0	253.4	0.766
June	146.2	77.30	24.77	135.9	131.0	201.1	188.4	0.793
July	139.5	82.20	24.45	131.2	126.4	196.2	183.8	0.801
August	143.8	88.10	23.80	139.2	134.3	208.4	195.5	0.802
September	145.7	83.30	24.10	147.8	142.7	219.2	206.0	0.797
October	158.2	65.50	24.77	171.1	165.9	250.0	234.8	0.784
November	150.4	46.20	23.67	173.8	169.3	251.8	236.3	0.777
December	153.5	45.00	22.52	184.4	179.4	270.5	254.2	0.788
Year	1959.8	791.40	25.15	2051.1	1988.9	2977.8	2795.6	0.779

Legends: GlobHor Horizontal global irradiation
 DiffHor Horizontal diffuse irradiation
 T Amb Ambient Temperature
 GlobInc Global incident in coll. plane
 GlobEff Effective Global, corr. for IAM and shading
 EArray Effective energy at the output of the array
 E_Grid Energy injected into grid
 PR Performance Ratio

Fig 4.25. Main results for Grid-connected system

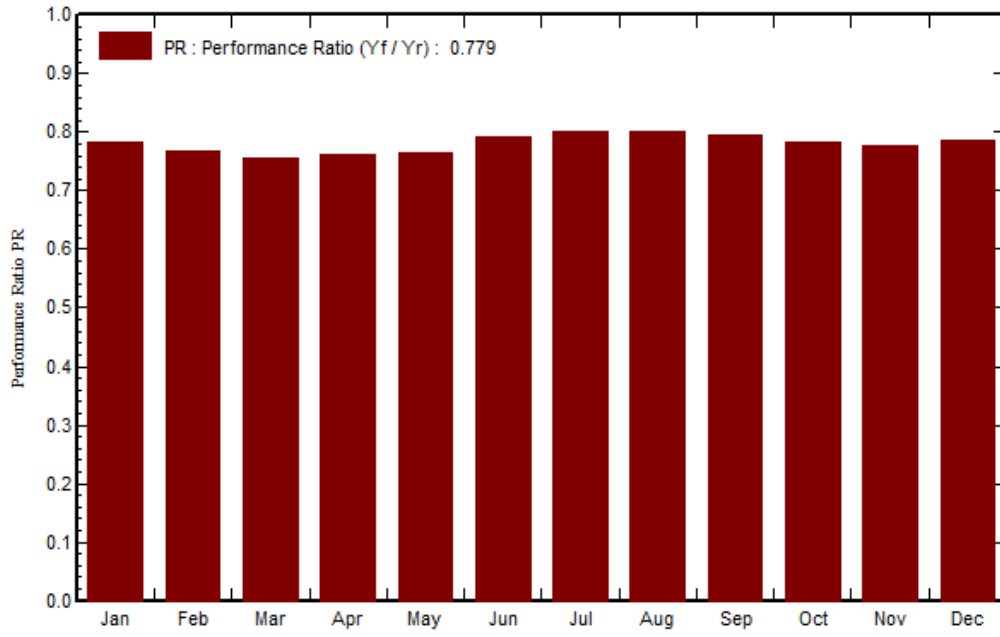


Fig 4.26. Performance Ratio (Grid-connected)

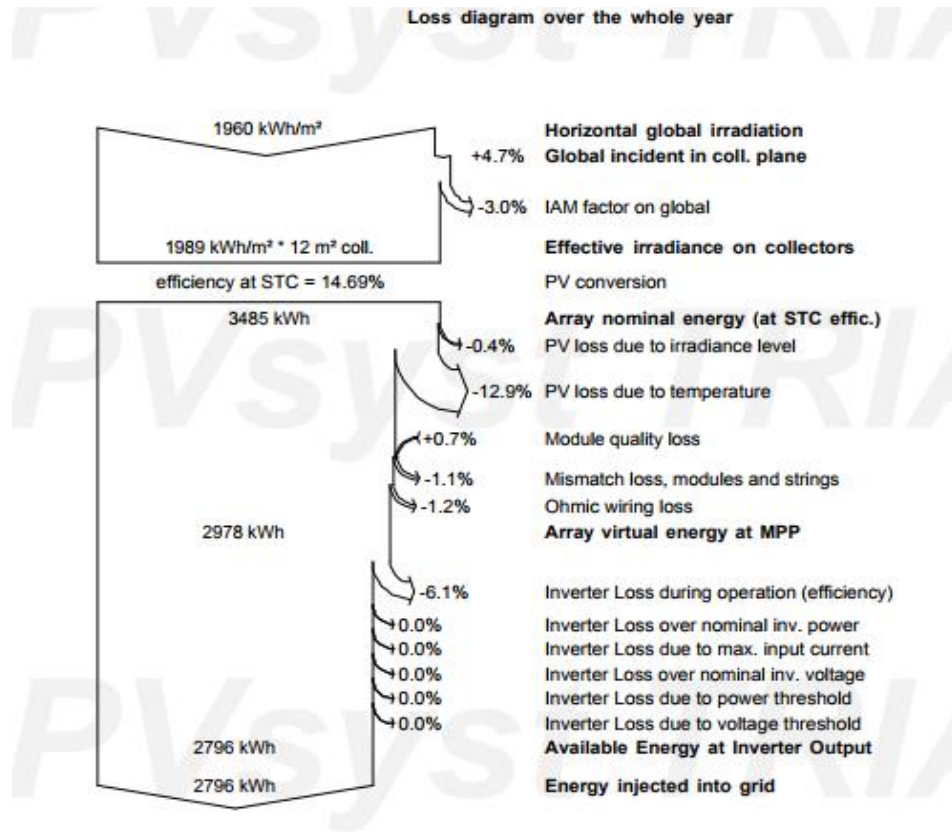


Fig 4.27. Loss Diagram for Grid-connected System

4.8. Matlab results

The graph shows the charge/discharge pattern of the battery system within a 24-hour period. Since the time of sunlight, energy from the PV system is stored in the battery, which ensures that excess amount of energies are not wasted should there be an increase in demand after that. The evening and at night are times through which the solar energy generation ceases; it is then that the battery releases its stored energy to the load for complete assurance of supply over the peak demand periods.

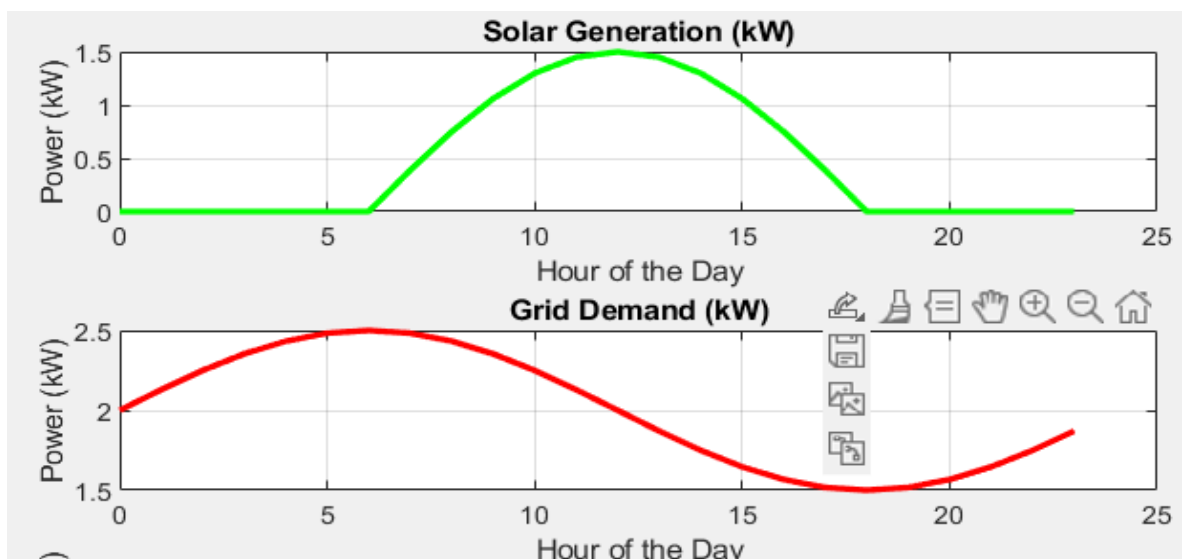


Fig. 4.28 Battery charge and discharge behavior.

The above pattern reflects the role of BSS in balancing energy generation and consumption. It fundamentally presents an efficient utilization of renewable energy in conquering the intermittent nature of solar power. Where this demand rises, especially in the early morning and evening, correspondingly, the discharge phase comes into action. This performance is, therefore, proof that BSS is capable of enhancing grid stability and optimizing the usage of energy in renewable energy systems.

Further, such a transition in charge and discharge, as depicted in this graph, reflects upon the system's reliability and adaptability in managing energy flow. This provides the kind of insight necessary for effective energy system design with maximum use of renewable energy and minimum use of non-renewable energy sources.

Battery SoC: Simulation, Including Charging and Discharging Behaviour

This figure presents the 24-hour SoC dynamics of a battery storage system, elaborating the interactions of charging and discharging periods within the variable conditions of energy demand and solar generation. The SoC signifies the residual percentage of battery capacity within the defined operation limits of minimum SoC (20%) and maximum SoC (80%) for optimal batteries in terms of both safety and efficiency.

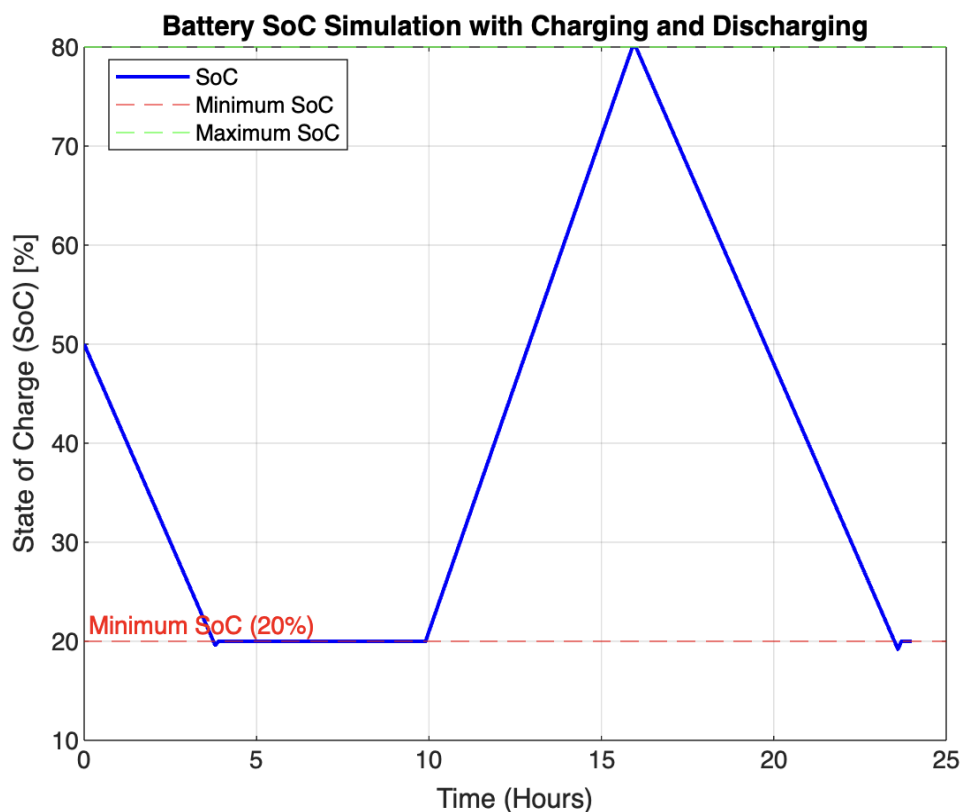


Fig. 4.29 Charging and Discharging Behaviour.

Main Observations and Phases

Initial Discharge Phase (0–5 h):

Energy demand during the early morning hours is higher than that generated by the solar panels. Hence, the battery storage has to utilize the stored energy

The SoC goes down from its initial 50% to the threshold value of 20%, reflecting the role of the battery in sustaining the energy supply in hours of low generation

Resting Phase (5–10 h):

Once this predefined minimum SoC threshold is reached, the battery stops discharging to prevent what is called deep discharge—a painful state that diminishes both the life span and efficiency of a battery.

Thus, the system enters a sort of 'protective rest' and is paused until enough energetic input can start its recharging.

Charging Phase (10–15 h):

Peak solar generation at noon allows the battery to recharge effectively, and the SoC increases from 20% to a peak of 80%.

This period puts forward the ability of a battery to store excess energy produced by the solar panel for use at times of generation shortfall, thus maximizing the use of renewable resources.

Second Discharge Period (15–24 hrs):

When solar energy generation is zero, as in late afternoon and night, the battery starts discharging and supplies the demand for energy in those hours of nil generation.

The SoC gradually decreases to the minimum value at the end of the cycle, wherein the system is ready for the next charge period.

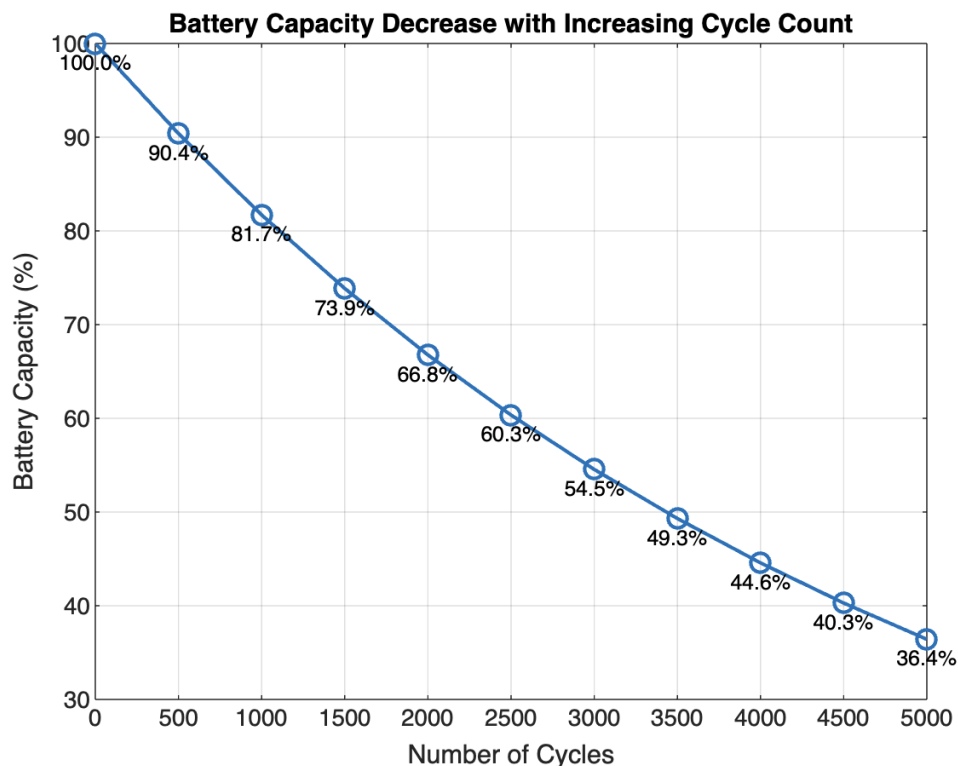


Fig. 4.30 Battery capacity vs. NoC

This graph shows the capacity (theoretical) versus cycle number for a continuously degrading battery: from the 100% working condition at the first cycle to 36.4% after 5000 cycles.

Battery degradation or aging results from internal, non-reversible, chemical degradation processes, such as electrode wear, for instance.

Key Perception: Thus, the State of Charge should be kept within its optimal operating range of 20% to 80% to avoid degradation of the batteries and to extend their lifetime. Such a

strategy reduces the risk for deep discharges and overcharges that speed up the wear-out processes, which in turn decrease the efficiency of the battery with time.

CHAPTER FIVE

DISCUSSION AND CONCLUSIONS

This chapter synthesizes the findings from the simulations, analyses, and literature review in a comprehensive discussion of implications of BSS in modern energy systems. It provides further elaboration on technical, economic, and environmental insights, while considering policy and market considerations. Furthermore, it reflects on limitations of the study and proposes directions for future research.

5.1 Technical Insights and Innovations

The research demonstrates that BSS integration significantly enhances the functionality and resilience of renewable energy systems. Key technical insights include:

1. Enhanced Grid Stability and System Resilience

BSS reduce the variability of renewable energy sources by smoothing voltage and frequency fluctuations. The simulations also reveal that systems designed with high-efficiency lithium-ion batteries provide reliable energy autonomy, especially during adverse weather conditions. The four-day autonomy achieved in the design is indicative of a robust solution to maintain uninterrupted power supply.

2. System Optimization and Energy Utilization

Advanced tracking systems, such as dual-axis trackers, have shown up to 40% improvement in energy capture efficiency over fixed-tilt systems. The integration of Maximum Power Point Tracking (MPPT) charge controllers further ensures optimal energy flow within the system, reducing losses and maximizing utilization.

3. Emerging Technologies in Energy Storage

While lithium-ion remains the dominant technology, other options include solid-state and sodium-ion batteries, which hold great promise for overcoming cost, safety, and recyclability concerns. Their ongoing development might redefine the energy storage landscape and make BSS more feasible and sustainable.

4. Scalability and Adaptability

BSS have scalable designs for various applications, ranging from rural off-grid systems to urban grid-connected installations. This makes BSS versatile for different energy applications.

5.2 Economic Feasibility and Challenges

The economic review emphasizes that even though the initial investment in BSS is high, there is a potential for cost-effectiveness during its lifecycle. The major economic highlights are:

1. Lifecycle Cost Analysis (LCCA)

The LCCA for the study has brought out that while standalone systems require substantial upfront investment, they eventually pay back by way of reduced dependence on external sources of energy. Grid-connected systems, although cheaper upfront, do not have the resilience or independence associated with standalone systems.

2. Policy and Financial Incentives

The high capital costs associated with BSS remain a critical barrier to widespread adoption. Government policies in the form of subsidies, tax incentives, and financing mechanisms like green bonds are vital for accelerating market penetration.

3. Economic Benefits Beyond Cost Reduction

Applications of BSS include peak shaving and energy arbitrage, offering added revenue streams to both energy producers and users. Besides, the contribution of these batteries in ancillary services markets contributes to increased grid reliability and facilitates the proper dynamics of energy markets.

5.3 Environmental Impacts and Sustainability

BEES make significant contributions to environmental sustainability in several keyways, enabling transition to cleaner energy systems. Some highlights include:

1. Carbon Emission Reductions

BSS enable higher integration of renewables into the grid, hence reducing fossil fuel consumption and resulting in major greenhouse gas emission reductions.

2. Advances in Material Efficiency

New battery technologies put emphasis on resource efficiency and recyclability, hence responding to environmental concerns linked to raw material extraction and waste management.

3. Decentralization and Reduced Transmission Losses

Rooftop PV systems with integrated BSS represent a movement toward decentralized energy solutions. These systems enhance local energy resilience and reduce transmission losses, thus moving toward a fairer energy distribution concept.

5.4 Policy and Market Implications

The findings bring to the fore the need for a supportive policy framework that will help ensure the adoption and integration of BSS. Recommendations include:

1. Standardization and Regulation

Clear and uniform standards for BSS deployment will reduce market entry barriers and encourage investment. This includes safety certifications, performance benchmarks, and streamlined permitting processes.

2. Incentivizing Innovation

Investments in research and development should prioritize next-generation battery technologies and innovative system designs to overcome existing technical and economic limitations.

3. Integration into Energy Markets

Policies that favor the participation of BSS in ancillary services and balancing markets will create the greatest value for BSS to the grid. An example includes capacity payments for frequency regulation services, which could incentivize broader adoption.

5.5 Limitations of the Study

However, despite this wider coverage, this work also suffers a number of limitations including the sole reliance on simulated data without real-world operational constraints. Further work, especially through pilot projects or case studies, is necessary to establish the wide generalizability of these results.

5.6 Future Research Directions

Some avenues that might be usefully explored:

- Cost-Effective Alternative Development

Research into sodium-ion, zinc-air, and other emerging battery chemistries can address cost and resource constraints.

- Advanced Control Strategies

Integration of artificial intelligence and machine learning for predictive maintenance and real-time energy management will further enhance BSS efficiency.

- Socioeconomic Impact Studies

Analyzing the broader socioeconomic benefits of BSS deployment, including job creation and energy equity, will help in policy decisions.

Conclusion

The design, simulation, and analysis of BSS integrated with standalone and grid-connected PV systems are comprehensively presented in this work. Optimum system configurations were developed using advanced computational tools like PVsyst to address the specific energy demands of rural and urban scenarios. This research underlines not only the technical feasibility of such systems but also the economic and environmental implications, thus paving the way for scalable and sustainable energy solutions.

Advanced BSS simulations results give a number of the parameters that influence the system's reliability, mainly at low solar insolation. Preventions of CO₂ emission are standing at about 1.83 tons in rural settings and about 64.416 tons in urban applications over the 30-year life span. Conclusively, it has been proven that BSS will help not only in enhancing energy resiliency but also contribute significantly to mitigating climate change through greenhouse gas emissions reduction.

Advanced battery technologies, such as lithium-ion batteries that were incorporated into the design, finally let the system realize its maximum energy storage and utilization. The selected batteries were of high efficiency, long life, and relatively inexpensive, hence very apt for stand-alone and hybrid applications. The tracking systems have been another very instrumental element in increasing the energy capture by PV configurations, hence ensuring the demands for energy can be reliably met in a sustainable way.

In as much as this contribution gives a roadmap toward the improvement of energy access and standards of living in regions with unreliable or highly inadequate grid infrastructure, the contribution this research makes toward societal benefit cannot be overestimated. The contribution assuredly catalyzes the transition of the world toward renewable energy systems, rhyming with international efforts for the attainment of energy equity and sustainability, given the sustainable and economically viable energy solutions that the study avails.

Core integration of technical innovation, environmental stewardship, and economic viability in the design of energy systems is underlined in this work. The findings of this

research are sure to chart a course for further work on renewable energy systems and provide scalable solutions to emerging global demands for clean and resilient supplies of energy.

REFERENCES

Journals and Papers:

1. Chen, H., Cong, T.N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, 19(3), 291–312.
2. Denholm, P., Ela, E., Kirby, B., & Milligan, M. (2010). The role of energy storage in balancing the electricity grid. National Renewable Energy Laboratory (NREL), Technical Report NREL/TP-6A2-47187.
3. Eyer, J., & Corey, G. (2010). Energy storage for the electricity grid: Benefits and market potential assessment guide. Sandia National Laboratories, Technical Report SAND2010-0815.
4. Liu, H., Wei, Z., He, G., & Zhou, Z. (2018). Economic analysis and optimization of battery energy storage system for frequency regulation in electricity markets. *Energy*, 144, 879–890.
5. Luo, X., Wang, J., Dooner, M., & Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, 137, 511–536.
6. Salahi, S., et al. (2016). Design and optimization of hybrid micro-grid systems using HOMER software. *Renewable Energy Journal*, 6(3), 302–310.
7. Schmidt, O., Melchior, S., Hawkes, A., & Staffell, I. (2019). Projecting the future levelized cost of electricity storage technologies. *Joule*, 3(1), 81–100.
8. Sioshansi, R., Denholm, P., Jenkin, T., & Weiss, J. (2009). Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects. *Energy Economics*, 31(2), 269–277.
9. Su, W., & Wang, J. (2012). Energy management systems in microgrids integrating renewable energy and BSS. *IEEE Transactions on Smart Grid*, 3(4), 1864–1875.
10. Xu, Y., Li, W., & Hua, G. (2014). Optimization and economic analysis of battery energy storage systems in ancillary services. *Journal of Power Technology*, 8(1), 67–75.
11. Zakeri, B., & Syri, S. (2015). Electrical energy storage systems: A comparative review of technologies and market perspectives. *Renewable and Sustainable Energy Reviews*, 42, 569–596.
12. Rahman, F., & Alam, M.S. (2020). A review on recent advancements in battery energy storage systems for grid applications. *IEEE Access*, 8, 10846–10860.
13. Kandasamy, C.P., et al. (2013). Simulation of grid-connected solar photovoltaic systems using PVsyst. *International Journal of Renewable Energy Systems*, 7(2), 120–134.

14. Parvathy, Suresh et al. (2014). Performance evaluation of standalone solar PV systems under varying conditions using PVsyst. *Journal of Renewable Energy Technology*, 10(3), 45–56.

15. Barbour, E., & Wilson, I. (2014). A review of pumped hydro energy storage and battery systems in ancillary services. *Energy Systems*, 3(1), 49–66.

Books:

16. Dunn, B., Kamath, H., & Tarascon, J.M. (2011). Electrical energy storage for the grid: A battery of choices. *Science*, 334(6058), 928–935.

17. Kalogridis, G., Fan, Z., & Xiang, Y. (2019). *Smart Grid Technology and Battery Energy Storage Systems*. Springer.

18. Kim, J.G., & Lee, T.Y. (2018). *Advanced Energy Storage Systems for Power Grids and Renewable Energy Integration*. Elsevier.

19. Pulletikurthi, G., & Reddy, P.V. (2020). *Battery Energy Storage Systems: Principles and Applications in Modern Power Systems*. CRC Press.

20. Komoto, K., Breyer, C., Cunow, E., Megherbi, K., Faiman, D., & van der Vleuten, P. (2013). *Energy from the Desert 4: Very Large-Scale PV Power - State of the Art and Into the Future*. Earthscan/Routledge.

21. Smith, J.D. (2018). Analysis of renewable energy integration in modern power grids. *Electronic Theses and Dissertations*, 689. University of Denver. Retrieved from <https://digitalcommons.du.edu/etd/689/>

Reliable Internet Sources:

22. National Renewable Energy Laboratory (NREL). (2022). *Battery Energy Storage in Frequency Regulation and Balancing Services*. Retrieved from <https://www.nrel.gov>.

23. Azerbaijan Ministry of Energy. (2023). *Renewable Energy Development in Azerbaijan: Nakhchivan Solar Potential*. Retrieved from <https://www.minenergy.gov.az>.

24. European Commission. (2022). *Battery Storage in Modern Energy Systems and Electricity Markets*. Retrieved from <https://ec.europa.eu>.

25. World Bank Group. (2022). *Energy Storage Trends and Applications in Developing Countries*. Retrieved from <https://www.worldbank.org>.

26. Bloomberg New Energy Finance (BNEF). (2023). *Battery Cost Reduction Trends*. Retrieved from <https://about.bnef.com>.

27. International Energy Agency (IEA). (2023). *Grid Flexibility and Role of Battery Energy Storage Systems*. Retrieved from <https://www.iea.org>.

28. MIT Energy Initiative. (2022). *Economic Benefits of Battery Storage in Balancing Renewable Energy*. Retrieved from <https://energy.mit.edu>.

29. International Renewable Energy Agency (IRENA). (2022). *Battery Storage for Renewables: Market Status and Technology Outlook*. Retrieved from <https://www.irena.org>.
30. Energy Storage Association. (2023). *Battery Storage Technologies for Electricity Markets*. Retrieved from <https://www.energystorage.org>.