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UNIVERSITY OF VAASA

Title: “Analyzing technical and financial benefits of investing in solar plus battery hybrid plants to replace new or aging fossil power plants”

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Abstract

The increasing environmental impact of entirely fossil fuel-based power generation, rising fuel tariffs, and growing power conservation concerns have multiplied the worldwide transition to renewable power system. In Bangladesh, electricity generation is based closely on getting traditional fossil fuel like natural gas, oil, and coal. This paper addresses the alternative of three distributed fossil fuel generators supplying industrial electricity by designing a grid-interactive PV–battery energy system (BESS). In MATLAB/Simulink a 60 kW PV-based prototype system was first designed to observe power electronic performance, battery charging and discharging behavior, voltage regulation, reactive and active power, and system stability under real-time irradiance profile and load conditions. The equivalent hybrid system was then optimized within the NREL REopt platform to evaluate fossil fuel displacement, where it was modified to serve the same commercial load currently fed through three generators. Eleven scenarios representing specific plan cost structures, flexibility requirements, and deployment assumptions were analyzed to determine the most optimal appliance sizes, renewable energy penetration, and life-cycle economics. The results show that the designed solar PV–BESS equipment can reliably upgrade fossil fuel generators to maintain continuous energy supply, realize near-perfect renewable energy penetration, reduce operating cost and emissions, and transform the levelized cost of energy. The precise low-cost regional scenario in 2030 resulted in a first-class overall performance, resulting in almost 100% renewable energy supply with a predicted LCOE of almost 0.0357 USD/kWh. Overall, the findings show that the proposed PV–BESS hybrid equipment can successfully replace the current distributed fossil fuel generation with a technically robust and economically feasible renewable energy alternative.

Keywords: Solar photovoltaics (PV); battery energy storage system (BESS); hybrid renewable energy system; MATLAB/Simulink; techno-economic optimization; renewable energy integration; voltage source converter (VSC).

Table of Contents

List of Figures

List of Tables

Abbreviation

BESS	Battery Energy Storage System
BMS	Battery Management System
CAPEX	Capital Expenditure
DC	Direct Current
DC-link	Direct Current Link
D-Q	Direct-Quadrature Axis
DG	Distributed Generation
EV	Electric Vehicle
LC Filter	Inductor-Capacitor Filter
LCOE	Levelized Cost of Energy
MATLAB	Matrix Laboratory
MPPT	Maximum Power Point Tracking
O&M	Operation and Maintenance
PCC	Point of Common Coupling
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy System
SoC	State of Charge
THD	Total Harmonic Distortion
VSC	Voltage Source Converter
kW	Kilowatt
kWh	Kilowatt-hour

Chapter 1

Introduction

1.1 Background of the Study

The global energy sector is currently experiencing significant changes that are caused by the necessity to decrease greenhouse gas emissions, increase energy efficiency, and ensure sustainability. Traditionally, electricity has been produced using fossil fuels like coal, natural gas, and oil because of the relatively high energy density of those fuels and available infrastructure. However, emissions produced by fossil fuels, as well as climate change and environmental degradation, have raised concerns and created pressure to move away from fossil fuels towards greener energy options [1]. Moreover, fuel price fluctuations and geopolitical events make nations vulnerable to such factors [2].

Regarding Bangladesh, there is a set of particular problems in the energy sector. Despite the widespread electrification of the country, Bangladesh still experiences problems with power reliability, frequent blackouts, and heavy dependence on imports of fossil fuels. The current energy mix is dominated by natural gas, oil, and coal, accounting for the majority of electricity production [3]. The current energy dependency puts pressure on foreign exchange reserves and makes the country vulnerable to supply interruptions and market fluctuations [4].

Furthermore, many old and inefficient fossil-fuel power plants increase operating costs. They fail to cope with increases in electricity consumption due to industrialization, urbanization, and population growth in Bangladesh [5]. There is thus a necessity to find alternative energy sources that can provide a reliable energy supply at reasonable costs.

One of the best options for solving the problem is the application of renewable energy technologies based on solar energy. The geography of Bangladesh makes it possible to use the abundant potential of solar irradiation in order to generate power [6]. However, the intermittent character of solar energy is one of its major disadvantages, as energy production may fluctuate according to the weather conditions and the daylight hours. Such energy fluctuations may cause disruptions in the energy supply if they are not addressed.

A solution to the problem could be found by integrating batteries with PV modules to create hybrid energy systems. With BESS, it is possible to store the surplus of energy generated when solar irradiation intensity is high and use it when the amount of energy decreases, or consumption goes up [7].

Besides the techno-performance evaluation, the implementation of the large-scale renewable energy system requires techno-economic optimization to determine system capacity, life-cycle cost-benefit, and the system's resilience performance. Optimization techniques like REopt, which has been developed by the National Renewable Energy Laboratory (NREL), have been widely applied for renewable energy optimization and sizing of hybrid system design.

Not only does the current generation of hybrid technology offer active power generation, but it is also possible for this generation of technology to generate reactive power using sophisticated converters such as Voltage Source Converters (VSCs). Such a feature is important for maintaining voltage stability and power quality in an electricity network; these roles have traditionally been provided by fossil fuel-based generating stations [8]. Thus, a good solar-battery hybrid system will be able to emulate the operation of fossil-fuel generators.

1.2 Problem Statement

Although there is increased awareness about renewable energy technology, the wide implementation of solar and battery hybrid systems in Bangladesh is hampered by multiple technical and economic problems. The national power system is based on fossil-fuel power generation facilities that account for a considerable share of energy production in the country [9]. As a result, high carbon dioxide emissions, increased operating expenses, and vulnerability to foreign fuel market changes have emerged.

Another issue associated with switching from fossil fuels to renewable energy sources concerns system reliability. Conventional power stations produce not only active power but also provide reactive power compensation that is needed for the effective regulation of the electric voltage. Most renewable energy systems, especially solar PVs, cannot perform this task and therefore cannot be used as an alternative source [10].

Another challenge in implementing hybrid systems refers to their economic viability. Although the costs of using solar PV and battery systems have been decreasing lately, the price tag of a hybrid configuration is still rather expensive when compared to conventional power plants [11].

In addition, current literature focuses mainly on either one aspect or another. In other words, researchers tend to emphasize either the technical performance of hybrid systems or their economic aspects. Also, there is a lack of research concerning the design and development of hybrid systems that would mimic the operation of fossil-fuel power plants and provide both active and reactive power compensation. Therefore, this thesis aims to develop a model of a hybrid system that integrates dynamic simulation and optimization techniques in order to prove that such systems could successfully replace traditional power stations in providing similar functions at a lower cost.

1.3 Objectives

The main objective of this study is to investigate the technological and economic feasibility of using hybrid solar-battery energy systems as alternatives for new or existing coal-fired power stations in Bangladesh. The investigation will entail an analysis of the performance of the proposed system in different environmental and loading scenarios, as well as the economic feasibility of the system through cost optimization [1], [2], [19].

The investigation will examine the possibility of meeting the load demands and maintaining the stability of the power grid with active and reactive power supply by hybrid systems [21]. Furthermore, the research aims to determine the technical and economic feasibility of installing solar systems coupled with batteries through optimization using the REopt model for various cost and resilience scenarios [33]. The research seeks to establish the best system design that can help decrease the LCOE without compromising the reliable integration of renewables into the grid [6], [26].

1.4 Scope of the Work

This paper will focus on the development and simulation of an architectural framework for the PV-BESS grid connection system using MATLAB/Simulink software for technical evaluation of its prototypes and REopt software for techno-economic assessment of its use at utility scale. The MATLAB/Simulink analysis will focus on converter dynamics, voltage regulation, BESS functionality, and integration of renewable generation based on different irradiance and load conditions [14], [18], [20].

Feasibility studies on the deployment of this system include eleven scenarios developed using REopt under different future cost assumptions, resilience-based operations, low and high renewable deployment cost assumptions, and discount rate sensitivity tests [35].

Environmental impact assessment will focus mainly on the penetration level of renewable energy and possible reductions in emissions. Full-scale lifecycle environmental assessment and grid market operations are beyond the scope of this paper.

1.5 Significance of the Thesis

The research adds value to existing knowledge about hybrid renewable energy systems by offering a comprehensive analysis of the technical and economic aspects of such systems. Through the demonstration of the potential of hybrid energy systems to mimic the operation of traditional fossil fuel power generation systems, the research highlights a viable path towards sustainable energy systems [4], [5].

It is expected that the research outcomes will guide decision-making processes for stakeholders in deploying hybrid energy systems through the provision of concrete information about their potential advantages. For instance, it shows the potential of solar power systems to minimize dependency on fossil fuels and reduce energy costs.

The inclusion of REopt-based scenario analysis further strengthens the research by providing realistic large-scale deployment insights under multiple future economic and resilience conditions.

1.6 Structure of the Thesis

The rest of the thesis is structured as follows.

Chapter 2 there will be provided an extensive review of the relevant literature will be provided, addressing the issues of hybrid renewable energy systems, PV generation, BESSs, converters, and techno-economic optimization.

Chapter 3 will describe the methodology, including the structure of the MATLAB/Simulink model developed, the configuration of the system studied, and control strategies employed, as well as the REopt-based optimization approach.

Chapter 4 covers the result and analysis.

Chapter 5 will present details concerning the implementation of the proposed hybrid renewable energy system, including PV generation modeling, BESS modeling, and converter design, as well as the architecture of system control.

Chapter 6 highlights the relevance of the results in terms of substituting fossil fuels.

Chapter 7 serves as a conclusion to this study.

Chapter 2

Literature Review

2.1 Introduction

The transition from fossil fuel-based power generation to renewable energy has recently become one of the key areas of modern power engineering development, motivated by environmental reasons, energy security requirements, and long-term economic factors. Hybrid renewable energy sources, such as solar photovoltaics (PV) integrated with battery energy storage systems (BESS), have been identified as promising technologies that may overcome natural variability while maintaining energy system performance and stability [12].

Over the last few years, there has been a significant drop in the costs of both solar PV and battery markets around the globe, contributing to the financial efficiency of hybrid systems. The LCOE of solar PV has significantly decreased owing to the evolution of technology, economies of scale, and innovations in production processes [26], [30]. At the same time, battery storage costs have been substantially decreasing due to the wide application of these technologies in electric transport and energy networks. Thus, cost ranges may be considered for solar PV and battery storage systems during techno-economic analysis, usually specified as low-, reference-, and high-cost alternatives [35].

Apart from the economic benefits of hybrid systems, high renewable energy systems possess operational properties that cannot be attributed to conventional fossil fuel power stations [21]. Specifically, renewable energy generation varies depending on weather conditions, possesses lower inertia, and requires more intensive use of power electronic converters to interface with the grid. Therefore, such systems require design features to provide voltage stability, frequency control, and reactive power support, which have been provided by synchronous generators in conventional power plants [15], [22].

Apart from validating performance aspects of electrical power, modern-day renewable energy planning demands large-scale techno-economic optimization analyses to determine benefits, feasibility, integration into the grid, and future possibilities. It is for this reason that tools like REopt, created at NREL, are frequently used in renewable energy planning.

This chapter presents an overview of the literature associated with solar PV, battery storage systems, and optimization approaches applied in hybrid configurations, along with their techno-economic evaluation as alternatives to conventional fossil fuel power stations. The purpose of the literature review is to investigate whether hybrid PV-BESS systems can mimic not only the generating capabilities of conventional power plants but also their operational properties, particularly in terms of active and reactive power generation.

2.2 Solar Photovoltaic Systems in Power Generation

Solar PV technology has experienced tremendous growth during the last decade due to falling prices and increased efficiencies. Solar PV systems convert solar energy directly into electrical energy using semiconductor materials, offering a green and sustainable source of energy compared to fossil fuels. According to recent studies, installed PV capacity globally has increased immensely, positioning PV technology as one of the quickest growing renewable energy sources [14].

The effectiveness of solar PV systems is greatly influenced by the environment, including solar irradiance, temperature, and shading effects. Changes in solar irradiance levels, particularly in places with seasonal weather variations such as Bangladesh, may result in unstable power generation levels [15]. In order to address these issues, sophisticated MPPT approaches have been introduced. One of the popular MPPT techniques employed today is the incremental conductance (INC) algorithm due to its ability to effectively trace the maximum power point despite fast changes in irradiance levels [16].

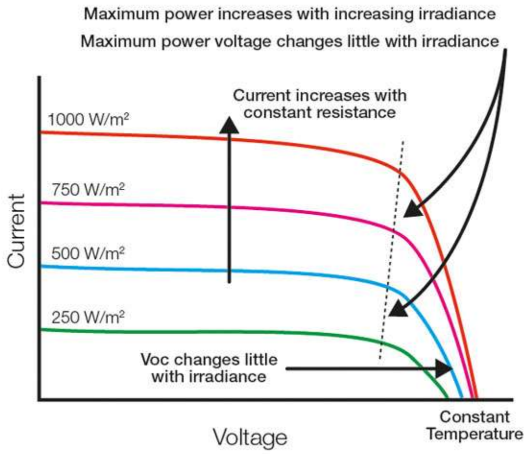


Figure 2.1: PV System Characteristics under Varying Irradiance

Although these types of systems have many benefits, there are certain drawbacks associated with them because of their transient nature. The energy generated depends on whether it is daytime and is subject to weather conditions, thus making it difficult to provide a constant source of energy. Thus, PV systems on their own cannot replace thermal power plants [17].

2.3 Battery Energy Storage Systems (BESS)

Battery energy storage systems (BESS) play an important role in improving the performance of renewable energy systems. By storing excess energy during times of higher production and discharging the stored energy during times of lower production, BESS helps to overcome the intermittency associated with solar photovoltaics (PV) [18].

The lithium-ion battery appears as the most common technology for energy storage systems because of its high energy density, long life cycle, and declining cost [19]. When integrating BESS into the PV system, better load leveling, load shaving, and frequency control become possible, making such systems more appropriate for grid applications [20]. Apart from energy storage, BESS is able to provide ancillary services, such as voltage regulation and reactive power compensation, if coupled with power electronics converters.

Ancillary services are critical in maintaining the stability of the grid, especially in systems with high renewables penetration [21].

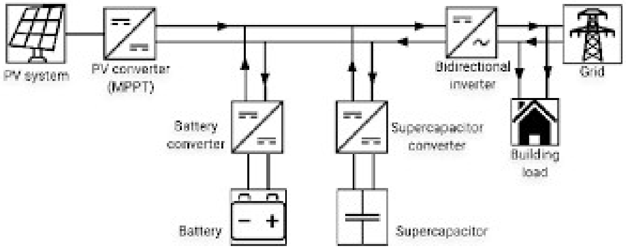


Figure 2.2: Battery Storage Integration in Hybrid Systems

However, the economic feasibility of BESS remains a significant issue. Although battery prices have fallen considerably during recent times, they still represent a considerable share of the total cost of the system. Therefore, proper sizing and control of BESS are crucial for making them economically viable [22].

2.4 Hybrid PV-BESS Systems

The use of PV generators together with Battery Energy Storage Systems (BESS) has received ample attention as one of the viable solutions to overcome deficiencies associated with renewable energy systems when operated alone. This combination improves renewable energy utilization, enhances operational reliability, and supports grid stability under varying load and generation conditions [23].

As far as grid-connected systems are concerned, they may function under various modes like grid support mode, isolated mode, and peak shaving mode. The interplay between the PV generation, BESS, and grid is carried out through an advanced control technique to make sure that the system runs effectively [24]. One of the key advantages of hybrid configurations is the ability to provide both active and reactive power. While PV plants generate mainly active power, the use of power electronics allows providing/reacting to reactive power requirements, which facilitates voltage regulation [25].

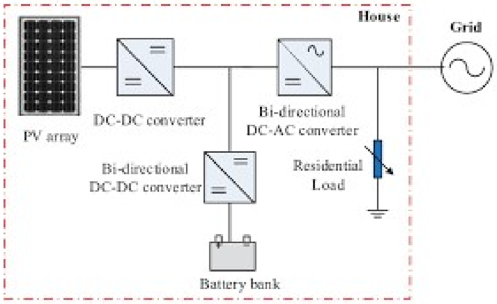


Figure 2.3: Typical Hybrid PV-BESS System Configuration

This feature becomes even more relevant in assessing the replacement of fossil fuel power plants. By definition, conventional power plants are able to produce not only active but also reactive energy, making their operation stable. Therefore, a new system must fulfill similar functions [26].

2.5 Power Electronics and Grid Integration

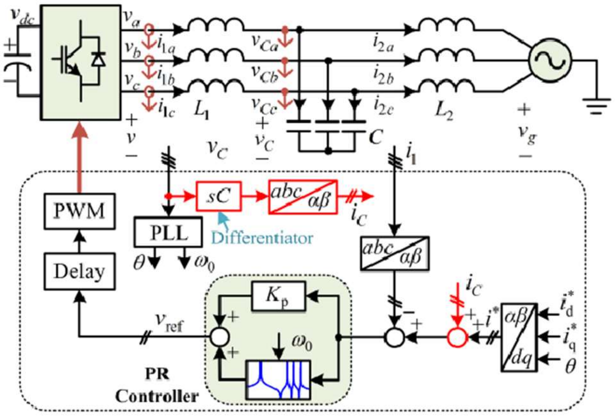


Figure 2.4: VSC with LC Filter for Grid Integration

The application of power electronics converters is essential in connecting renewable energy sources with the grid. Voltage-source converters (VSCs) have been widely used for DC-to-AC conversions in photovoltaic (PV) systems owing to their effectiveness and adaptability [27]. Through VSCs, there is enhanced control of active/reactive power, which ensures grid stability. The regulation of the output power flow and provision of voltage regulation are achieved by varying the output voltage's phase angle and amplitude [28]. The installation of LC filters enhances the quality of power through the reduction of harmonics. This factor is particularly important in high-switching-frequency applications where harmonics negatively impact the system's performance [29].

The reactive power control and filtering abilities of the voltage source converters allow the hybrid system to provide several grid stabilizing functions, which have normally been supplied by synchronous generators. This feature is crucial because renewable energy sources must be able to replace traditional energy plants without compromising the stability of the grid [30].

2.6 Techno-Economic Analysis of Hybrid Systems

The cost-effectiveness of hybrid renewable energy systems is determined by indicators such as Levelized Cost of Energy (LCOE), net present value (NPV), and payback period [31]. However, among these, LCOE is the most common indicator since it provides an estimated cost per unit of energy produced in the lifetime of the system [32]. According to recent research, LCOE for solar PV plants has drastically decreased in recent years, making them more cost-effective compared to traditional energy generation methods [33]. In any case, hybrid systems with battery storage involve higher investment costs, which need to be optimized to be cost-effective [34].

As a solution to such complex aspects in the planning of renewable hybrid power plants, many techno-economic optimization methods have been developed, which can optimize different aspects such as the dimensioning of the plant, operations, lifetime costs, and resilience performance. REopt is one such platform developed by NREL that has gained considerable recognition in the analysis of renewable energy under different deployment scenarios in the future.

REopt optimizes photovoltaics size, battery size, share of renewable energy, grid interactions, life-cycle savings, and resilience against outages. This software platform has found wide applicability in the analysis of renewable energy for commercial buildings, microgrids, and utility-scale hybrid renewable power plants [35].

2.7 Research Gap Analysis

Although there have been numerous studies on hybrid PV-BESS systems, several limitations remain in the body of knowledge. Most studies focus on either technical or economic aspects, but rarely combine both perspectives. Furthermore, the ability of hybrid systems to mimic the behavior of fossil-based power generation facilities concerning active/reactive power supply may not be sufficiently considered [36]. Also, many researchers use overly simplistic models to represent loads, which limit the practical relevance of their results. Additionally, limited research has been conducted on integrating prototype-scale electrical validation with utility-scale techno-economic optimization under multiple future renewable deployment scenarios and resilience-oriented operating conditions. Another limitation is the lack of scholarly works concerning developing nations like Bangladesh, whose energy needs differ from those of developed countries [37].

2.8 Summary

This chapter aims to present the existing literature on solar photovoltaic systems, battery energy storage systems, integration of hybrid systems, and techno-economic assessment [20], [33]. The findings highlight the possibility of implementing hybrid systems consisting of PV-BESS for obtaining reliable and sustainable sources of energy, thus decreasing the use of fossil fuels [6], [7] . However, some gaps in research have been identified, namely those associated with reactive power provision and techno-economic integration. The insights gained from the literature review provide the foundation for developing the prototype-scale MATLAB/Simulink validation framework and the REopt-based techno-economic optimization methodology employed in this research.

Chapter 3

Methodology

3.1 Introduction

The methodological framework for assessing the technical and financial viability of substituting hybrid solar plus battery systems for newly constructed or outdated fossil fuel power plants in Bangladesh is presented in this chapter. The two complementary parts of the methodology form its framework:

1. Techno-economic optimization using the REopt platform, and
2. Technical performance validation using MATLAB/Simulink.

The thesis primary analytical tool is the REopt model MATLAB/Simulink is only utilized to verify operational behavior such as power flow, battery dispatch and voltage stability. This structure guarantees that the thesis stays a techno-economic study rather than a simulation-centric work. Although the Simulink implementation is carried out in small sizes, the control and operational concepts used in the model can scale up with minor modifications in the engineering field [1], [6], [9].

3.2 REopt Optimization Techno-Economic Optimization Framework

The U.S. created REopt a techno-economic platform for decision support. The S. Laboratory for Renewable Energy (NREL). It is extensively utilized for resilience-oriented energy planning microgrids hybrid renewable systems and the best sizing of distributed energy resources [33]. REopt finds the most economical set of technologies to satisfy operational financial and policy constraints while meeting energy demand. REopt is particularly suitable for Bangladesh because it can consider various cost assumptions when evaluating PV and battery sizing. When solar irradiance varies optimize dispatch strategies. Calculate lifecycle savings LCOE CAPEX and OPEX. Evaluate the performance of resilience during outages. Calculate the emission reductions in comparison to baselines using fossil fuels [26], [29].

To evaluate the feasibility of large-scale deployment of the proposed renewable-hybrid system, The REopt methodology was applied to determine the optimal combination of installed photovoltaic capacity, battery power, and battery energy, along with the optimal operation strategy, under different assumptions regarding future costs and deployment.

In this research, a total of eleven REopt-based scenarios were evaluated. Due to high-cost uncertainty, we designed a system based on varieties of scenario assumption. We take regional cost scenario, using a cost estimate of India, a regional market leader and a neighbor to Bangladesh, to represent 2030 optimistic cost of system in Bangladesh. The global average cost is used to represent the high-cost scenarios of Bangladesh. For each case, we created three scenarios, a reference scenario, the high and low-cost cases created by modifying the reference cost by adding/subtracting 20% of the reference cost. We also include other scenarios representing resilience-based operation assumptions, varying discount rates, and present cost scenarios. Table 3.1 provides all scenario names and related costs and other assumptions.

Table 3.1: Description of REopt Optimization Scenarios

Scenario No.	Scenario Name	Description
1	2030 Low Cost Regional	Regional low-cost future renewable deployment scenario
2	2030 Reference Cost Regional	Baseline regional renewable deployment scenario
3	2030 High Cost Regional	High-cost future renewable deployment under regional assumptions
4	2030 Low Cost Global	Global low-cost renewable deployment scenario
5	2030 Reference Cost Global	Baseline global renewable deployment scenario

6	2030 High Cost Global	High-cost global renewable deployment scenario
7	2030 Reference Cost Regional High Resilience	Resilience-oriented renewable deployment scenario
8	100% RE Reference Cost Regional	Fully renewable electricity deployment scenario
9	2025 Reference Cost Regional	Near-term regional renewable deployment scenario
10	2025 Reference Cost Global	Near-term global renewable deployment scenario
11	2030 Reference Cost Regional (10% Discount)	Financial sensitivity analysis using modified discount rate

Here, REopt is used to replicate eleven scenarios, including low-cost, reference-cost, high-cost, resilience-based, and discount-rate-sensitivity cases.

3.3 REopt Mathematical Formulation

REopt solves a mixed-integer linear optimization problem. The core formulation is summarized below.

Objective Function

If we assume:

- C_{PV} = PV capital cost
- C_{BESS} = Battery capital cost
- $C_{\text{O\&M}}$ = Annual operation & maintenance
- C_{Grid} = Cost of imported electricity
- C_{Fuel} = Fossil fuel cost (baseline comparison)
- S_{Export} = Revenue from exported energy

Then the model minimizes the total lifecycle cost:

$$\text{Minimize } C = C_{\text{PV}} + C_{\text{BESS}} + C_{\text{O\&M}} + C_{\text{Grid}} + C_{\text{Fuel}} - S_{\text{Export}} \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

If we assume:

- $G(t)$= Solar irradiance
- η_{PV}= Module efficiency
- β= Temperature coefficient

Then PV Output Constraint

$$P_{\text{PV}}(t) = A_{\text{PV}} \cdot \eta_{\text{PV}} \cdot G(t) \cdot [1 - \beta(T(t) - 25)] \text{ ………………………. (2)}$$

If we assume:

- C_t= Annualized cost
- E_t= Annual energy delivered
- r= Discount rate
- N= Project lifetime

Load Balance Constraint

$$P_{\text{PV}}(t) + P_{\text{dis}}(t) + P_{\text{grid}}(t) = L(t) + P_{\text{ch}}(t) \text{ ………………………. (3)}$$

LCOE Calculation

$$LCOE = \frac{\sum_{t=1}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \text{………………………. (4)}$$

This mathematical structure ensures transparency and reproducibility of the optimization process.

3.4 Scenario Development

Eleven scenarios are structured to mirror future cost structures, resilience needs, and policy conditions. These include:

- Low-cost PV
- Low-cost battery
- High-cost PV
- High-cost battery
- Combined low-cost
- Combined high-cost
- Resilience (24-hour outage)
- Resilience (48-hour outage)
- Discount rate sensitivity
- Grid-price escalation
- Fossil-fuel price escalation

Each scenario is run independently in REopt to establish optimal PV size, battery size, LCOE, and lifecycle savings.

3.5 Overall MATLAB Framework

The methodology of the research includes two main steps:

a. System Modeling and Simulation

Development of a precise hybrid PV-BESS model to analyze dynamic performance using MATLAB/Simulink.

b. Seasonal Variability-Based Performance Evaluation

Simulation of the system under various levels of irradiance seasonality to study the effect of environmental variability on system dynamics, stability, and reliability.

First, it should be noted that the suggested methodology combines techno-economic optimization, modeling, and system simulation. Unlike many previous studies that separate system performance analysis and techno-economics, the suggested approach establishes connections between them and considers optimization and performance as consecutive parts of the process [2], [6]. Thus, initially, optimal system configurations are determined via optimization. Then, these configurations are analyzed using modeling and simulation to test whether they are feasible or not.

Specifically, the whole procedure consists of several consecutive steps: techno-economic optimization of system sizing, system modeling using MATLAB/Simulink, and dynamic evaluation under various irradiance conditions. Each step requires information provided by the previous one to maintain consistency between the economy and engineering.

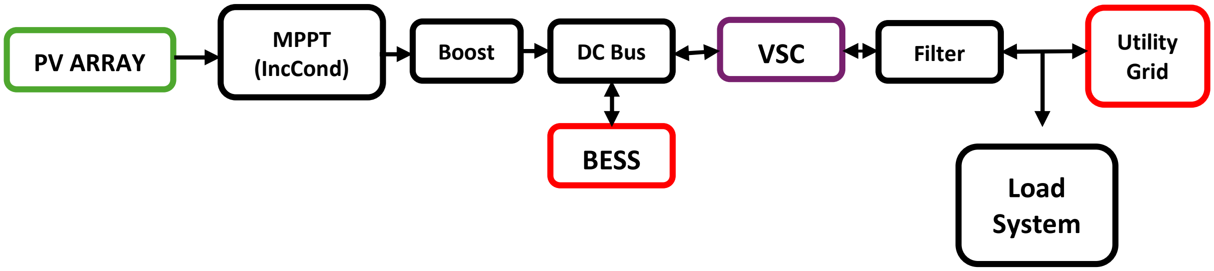


Figure 3.1: Overall Research Methodology Flowchart

First, the techno-economic optimization of the system sizing is performed using the REopt. The techno-economic optimization process involves multiple iterations during which many combinations of the capacity values are assessed using economic indicators, such as LCOE, satisfying system constraints including load requirements and permissible unmet energy demand.

At the second step, the optimized system configuration is implemented using MATLAB/Simulink for the creation of the detailed model of the PV-BESS system. The model includes such elements as PV modules, power electronic converters, battery energy storage dynamics, and connection to the grid. Dynamic simulation allows evaluating system behavior under transient conditions caused by abrupt load changes or variations in irradiance.

At the final step, system performance evaluation is conducted under various seasonal conditions by selecting representative periods with irradiance typical for rainy, summer, winter, and average annual seasons. In such a way, seasonal variability of the weather conditions affecting system behavior can be considered instead of creating independent scenarios. The performance analysis focuses on important indicators: PV generation dynamics, battery operations, DC link voltage stability, and energy exchange with the grid.

One of the most distinctive features of the suggested methodology is the unification of optimization and performance analysis, which allows designing a feasible and efficient PV-BESS system.

3.5.1 MPPT Algorithm (Incremental Conductance)

The Maximum Power Point Tracking (MPPT) technique is essential for the optimal operation of photovoltaic cells. For the current study, the Incremental Conductance (INC) algorithm is selected due to its high accuracy and performance in rapidly fluctuating environments [14].

The basic assumption underlying the INC algorithm is that at the maximum power point, the derivative of power with respect to voltage is zero:

$$\frac{dP}{dV} = 0 \text{ .... } (7)$$

As the output power of the PV cell is expressed through the equation P = IV, the above-mentioned condition can be written in another way:

$$dP/dV = I + V(dI/dV) = 0$$

From the above equation, it follows that:

$$\frac{dI}{dV} = -\frac{I}{V} \text{ .... } (8)$$

The equation provides for the determination of the maximum power point. Using the INC algorithm, the incremental conductance *(dI/dV)* of the PV cell is measured and compared with the instant conductance *(−I/V)*. As a result, depending on the outcome of the comparison, the operating point can be found to be either left or right of the maximum power point.

When *dI/dV* is greater than *−I/V*, the operating point is to the left of the MPP; when *dI/dV* is less than *−I/V*, the operating point is to the right of the MPP. When equality is attained, the operation takes place at the maximum power point [14].

In practice, the duty cycle of the DC-DC Boost converter is adjusted to control the operation of the PV cell in accordance with the algorithm. The advantage of the INC algorithm over such algorithms as P&O is the rapid attainment of the MPP and low oscillations of the system [14], [15].

3.5.2 Boost Converter Modeling

The boost converter increases the PV output voltage to a stable DC bus voltage (500V). The relationship between input and output voltage is:

$$V_{out} = \frac{V_{in}}{1-D} \text{ .... } (9)$$

Where D is the duty cycle.

The converter ensures:

- Stable DC link voltage
- Efficient power transfer to inverter

3.5.3 Battery Energy Storage System (BESS) Modeling

The battery is modeled using a controlled voltage source with state-of-charge (SoC) dynamics:

$$SoC(t) = SoC(t_0) + \frac{1}{C_{bat}} \int i_{bat}(t) dt \text{ ………………………… (10)}$$

Where:

- C_{bat} = Battery capacity

The battery operates in two modes:

- Charging (excess PV or grid power)
- Discharging (supporting load demand)

3.5.4 Voltage Source Converter (VSC) Control

The VSC converts DC power to AC and controls both active and reactive power.

Active power:

$$P = VI\cos\phi \text{ …………………….. (11)}$$

Reactive power:

$$Q = VI\sin\phi \text{ ………………………… (12)}$$

By controlling phase angle and current components:

$$I_d \rightarrow controls\ active\ power$$

$$I_q \rightarrow controls\ reactive\ power$$

This enables the system to mimic fossil plant behavior.

3.5.5 LC Filter Design

The LC filter removes harmonics and supports reactive power compensation.

Resonant frequency:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \text{ ……………………. (13)}$$

The filter ensures:

- Reduced THD
- Improved voltage waveform
- Reactive power injection capability

3.5.6 Load Modeling

Two load types are used:

Fixed Load:

$$P = constant$$

Variable Load:

$$P(t) = \begin{cases} 50kW & t < 2.5s \\ 100kW & t \geq 2.5s \end{cases}$$

Power factor:

$$PF = 0.95$$

This introduces realistic grid stress conditions.

3.5.7 Power Flow Control Strategy

The system follows a priority-based dispatch:

a. PV supplies load
b. Battery compensates deficit
c. Grid provides remaining power

Mathematically:

$$P_{load} = P_{PV} + P_{BESS} + P_{grid}$$

This ensures optimal utilization of renewable energy.

3.5.8 Reactive Power Consideration

Unlike conventional studies, this work explicitly evaluates reactive power.

$$Q_{total} = Q_{filter} + Q_{VSC}$$

This allows:

- Voltage regulation
- Grid support
- Fossil plant equivalence

3.5.9 Season-Based Simulation

To study the performance of the system under realistic environmental conditions, four different periods of time that represent different seasons are considered:

a. Rainy season

b. Summer season
c. Winter season
d. Average condition of the year

For each period, the following parameters are studied:

- Output of the PV module
- Behavior of the battery (charging/discharging and variation of its state-of-charge)
- Dependency on the grid
- Balance between generation, storage, and demand for power

The purpose of this study is to understand how the variability of the weather through the seasons affects the performance of the system.

3.6 Summary

The prototype based on MATLAB and Simulink modeling tools as well as REopt scenarios, represents different system levels of application and cannot be directly compared as identical numerical calculations [18]. While the Simulink model is designed to confirm the validity of proposed hybrid power system operations, the REopt scenarios refer to actual deployment plans of utility-scale power systems.

Also, establishing a clear fossil baseline against which all REopt scenarios are measured is essential to assessing the practicability of replacing fossil-fuel power plants with hybrid solar-battery systems. Since gas accounts for more than half of Bangladesh’s electricity generation and many units are over 20 to 25 years old operating with decreasing efficiency and rising fuel costs the baseline fossil system in this thesis represents a typical aging natural gas-fired power plant in Bangladesh. BPDB and Global Energy Monitor data show that older gas plants in Bangladesh have heat rates of 9000–11000 kJ/kWh (38) efficiencies of 32–38 percent and high variable operation and maintenance costs because of frequent maintenance needs [39]. The power industry is under a great deal of financial strain due to the recent sharp rise in fuel prices with LNG import prices ranging from 10 to 16 USD/MMBtu [40]. The IPCC and BPDB reports provide the emission factors for natural gas generation with CO_2 emissions of roughly 0.40–0.50 kg/kWh and significant NO2 contributions [41]. The lifecycle cost fuel expenditure and emissions of the fossil-fuel substitute are computed by REopt using these baseline parameters. The optimization model can measure the financial savings emission reductions and performance gains that occur when a hybrid solar-plus-battery system replaces a comparable fossil-fuel plant by creating this baseline. This guarantees that the techno-economic comparison is based on the practical operational features of Bangladesh’s current fossil fuel infrastructure.

Therefore, the prototype serves as a basis for a scalable system validation tool, whose behavior can be easily extended to larger renewable energy systems with minimal engineering adjustments.

Chapter 4

System Modeling and Simulation

4.1 Introduction

This chapter discusses the design and simulation of a solar PV-battery energy storage system (BESS) using MATLAB/Simulink. Contrary to the straightforwardness in analytical models, the simulation of the system considers the dynamics of the system, including power electronic converters, controllers, and their interconnection to the power grid to simulate the performance of the actual system [15], [18]. An important feature of the proposed system is that it can supply both active and reactive powers to the load. The ability to supply both active and reactive powers to the load is an important feature of the system that helps address one of the main challenges associated with conventional renewable energy systems in replacing fossil fuel power plants [24]. It includes a PV power generator, a boost converter with MPPT, a battery BESS, a VSC, an LC filter, and grid-connected loads.

4.2 Overall Simulink Model Description

This hybrid system model is designed using MATLAB/Simulink along with the Simscape Electrical toolbox. In this model, a modular approach is followed in which each module represents an individual function of the hybrid system. This overall structure consists of modules for power generation, conversion, storage, and load delivery.

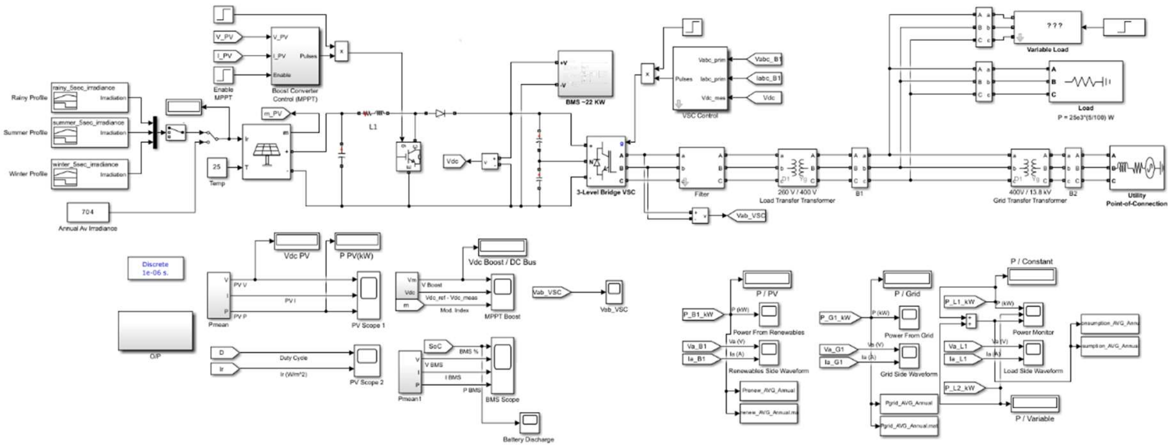


Figure 4.1: Complete Simulink Model of the Hybrid PV-BESS System

This system operates through the hierarchy of energy flow, which entails:

- The PV system is the main source of energy.
- The battery system acts as a backup in case of energy deficiency.
- The grid provides power if it is needed.

In the context of this hierarchy, energy flow makes sure that renewable energy sources will be used in an efficient manner without the use of grid electricity.

4.3 Photovoltaic (PV) Subsystem

A photovoltaic subsystem will be simulated using the SunPower SPR-305E-WHT-U photovoltaic module, which is highly efficient and has reliable operational properties. The basic scheme for the PV system is based on five interconnected modules, which consist of about 39 strings, thus resulting in a total power rating of 60 kW, with the direct current (DC) voltage being equal to 273.5 V.

However, it should be emphasized that the PV system implemented using MATLAB/Simulink is a prototype-scale setup used for verifying the performance related to power generation characteristics, converters, voltage regulation, and integration of renewable energy resources. The selected photovoltaic system capacity acts as a standard for evaluating the practicality of utility-scale renewable systems through REopt optimization techniques [33].

Therefore, the simulation model serves as a flexible tool that enables researchers to evaluate the dynamic performance of a system for different capacities.

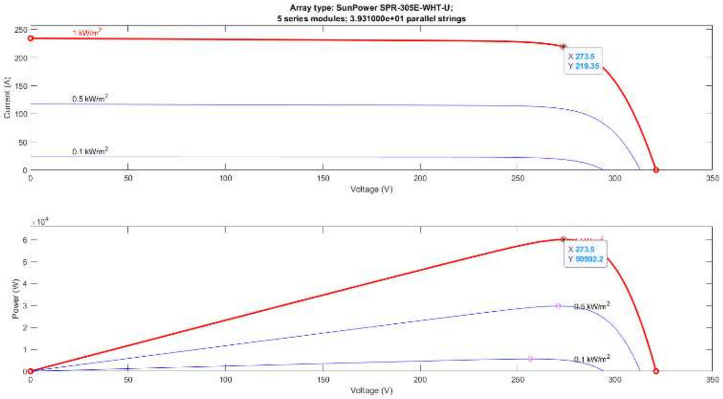


Figure 4.2: PV Array IV Characteristics

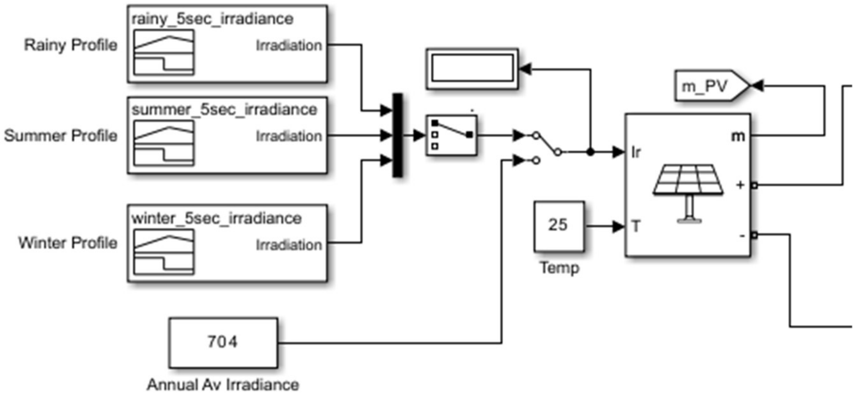


Figure 4.3: PV Array Subsystem

The irradiance and temperature parameters act as the input parameters for the PV subsystem, with different levels of values depending on the simulation scenario. In this case, four irradiance levels have been used, including rainy, summer, winter, and annual average. The outputs of the PV array include voltage, current, and power parameters.

In the process of simulation, the PV generation becomes zero at night on account of the profiles of diurnal cycle of solar irradiance. The discontinuity highlights the importance of providing energy storage means for maintaining the continuous supply of electricity.

4.4 MPPT-Based Boost Converter Subsystem

The PV output interface is connected to the boost converter with the INC MPPT control algorithm. The goal of this sub-system is to extract maximum power from the PV source while maintaining the stability of the DC link voltage. This controller always senses the PV voltage and current for finding the optimum operating point, and based on that measurement, it adjusts the duty ratio of the boost converter [15].

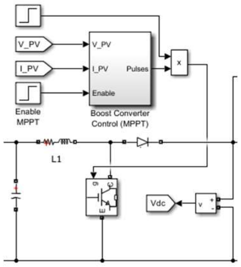


Figure 4.4: MPPT Controller and Boost Converter Subsystem

The Boost Converter increases the voltage of the Photovoltaic Cells from 273.5 volts to a stabilized voltage of 500 volts. The increase in voltage is essential in ensuring the optimal performance of the inverter and battery system. Based on simulation results, it can be observed that the duty ratio varies dynamically depending on the variation in irradiance levels.

4.5 Battery Energy Storage System (BESS)

The BESS is embedded in the configuration to provide additional energy balancing and improve the system's reliability. In terms of parameters, the battery works at a nominal DC voltage of 500 V with connection to the DC-link to enable two-way energy transfer. According to the reference configuration, the capacity and power rating of the battery are 22 kW, respectively.

The battery storage system embedded in the prototype Simulink model is used to demonstrate the validation of charging and discharging activities, DC-link regulation, load support, and energy management efficiency. Despite having a small battery storage capacity in the prototype, it can still be scaled to utility-scale capacity as determined through REopt optimization analysis.

The following two modes characterize the operation of the battery:

1. Charging mode: Starts working when the PV production surpasses the consumption of the load.
2. Discharging mode: Activates when PV generation is less than the demand of the load, allowing the battery to provide power to the load.

According to the literature, the initial state of charge is chosen to be 80%, which implies that the battery is partially charged. It is assumed that the initial SoC allows the battery to have enough charge to react to the demand instantly while leaving the ability to charge in case there is an excess of energy. It allows avoiding unrealistic assumptions of being fully charged and discharged.

To guarantee that the battery will work properly during the simulation, the control logic was implemented to limit the range of its SOC value.

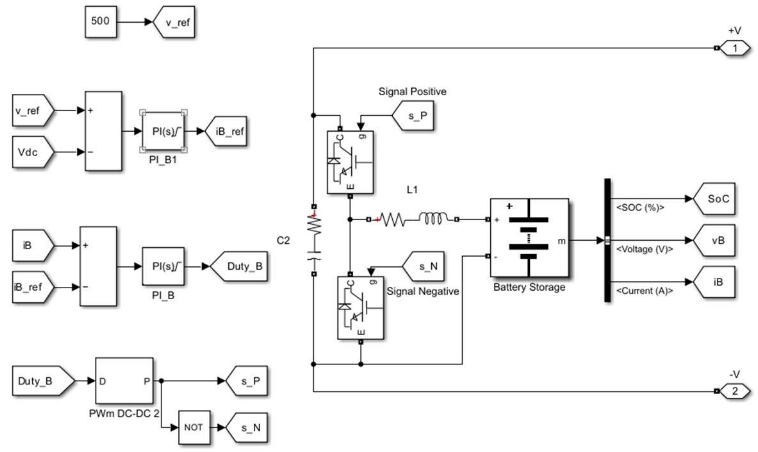


Figure 4.5: Battery Management System (BMS) Subsystem

4.6 Voltage Source Converter (VSC) Subsystem

The voltage source converter (VSC) acts to change DC voltages into three-phase AC voltages. In doing its job, the converter takes a DC input of 500 V and gives a three-phase AC output of 260 V. The control of the VSC is done by modulation of the converter, which helps to change the active and reactive powers.

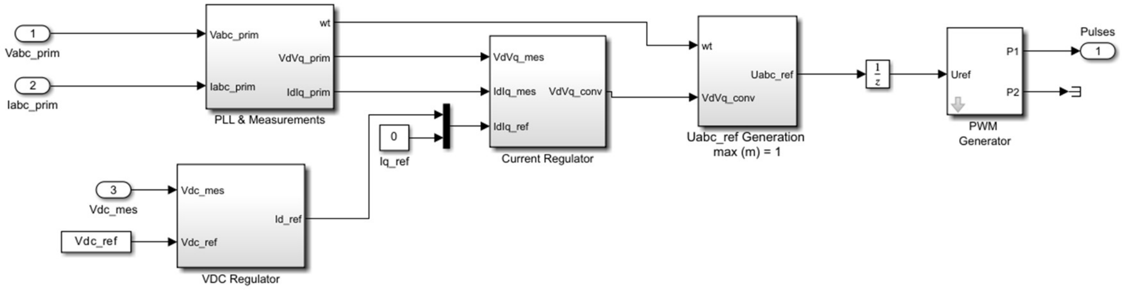


Figure 4.6: VSC Inverter Subsystem

Regulation of reactive power by the VSC is an important feature of this system, which makes it possible for the hybrid system to operate like a typical fossil fuel power station.

4.7 LC Filter Subsystem

The output of VSC has high frequency harmonics due to switching actions. To reduce the harmonics, the LC filter is used. This helps in smoothing the output waveforms.

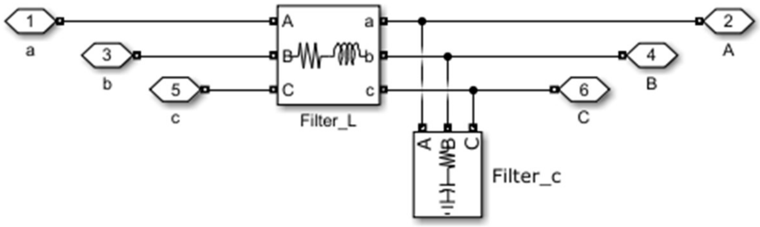


Figure 4.7: LC Filter Subsystem

In addition, the LC filter helps in providing reactive power compensation. Reactive power compensation is necessary for maintaining voltage stability. With the help of the filter, various reactive load conditions can be compensated.

4.8 Load Transfer Transformer

The load transfer transformer is used to boost the voltage level from 260 volts to 400 volts, which facilitates the supply of energy to the industrial loads. It helps to match the voltage levels of the inverter output and the load's requirements.

4.9 Load System Modeling

Two load models are used to simulate both the steady-state and transient operation of the system.

- **Fixed Resistive Load:** Fixed resistive loads represent the basic load requirement of the system in the steady-state operation of the system.
- **Dynamic Load:** A dynamic load, which represents varying demands, is created for transient testing purposes. In this case, a load from 50 kW to 100 kW is simulated over a period of 2.5 seconds while maintaining a power factor of 0.95.

It is important to note that this load profile is intended to be a step change to determine how the hybrid system responds when subjected to sudden load increases and decreases. This test is crucial to determine the dynamic capabilities of the system, such as voltage stability, power stability, and control performance when faced with transient situations. This test is critical in determining the performance of the renewable energy system under transient conditions [24].

It is also important to note that this particular model does not reflect a daily load profile; it rather acts as a simple test case for observing the system's performance under sudden changes in demand. During the techno-economic analysis process, more complex load profiles can be incorporated into the REOPT analysis.

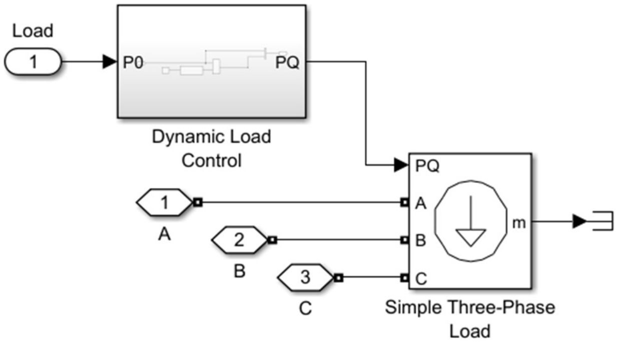


Figure 4.8: Dynamic Load Model Subsystem

4.10 Grid Integration Subsystem

Connection is ensured by the grid through the transformer and transmission lines. The grid acts as a backup power supply, providing electricity whenever the PV generation and batteries fall short.

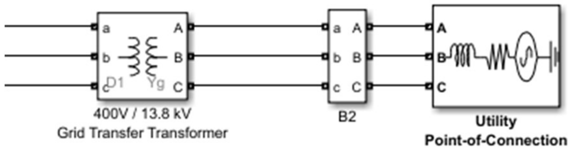


Figure 4.9 shows the Grid Connection Subsystem

Moreover, the grid accepts excess energy whenever generation exceeds consumption, thus ensuring equilibrium within the system.

4.11 Power Flow Monitoring

Power flows are measured mainly at two points:

- **Bus B1:** PV and battery power flows
- **Bus B2:** Grid power flows

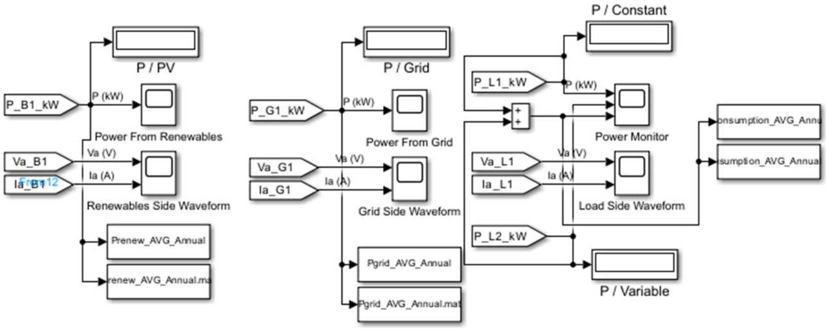


Figure 4.10: Power Flow Scope

This measurement makes it possible to conduct performance analysis and contribution analysis.

4.12 Key Features of the Modeling Framework

This subsection highlights the key functional characteristics of the proposed PV-BESS hybrid system, based on its architecture and control methodology.

- The PV generation subsystem acts as the main source of renewable energy, and it is connected to the DC link using a DC-DC boost converter that helps in controlling output voltage and achieving maximum power extraction.
- The BESS system is connected to the DC link and works in both charge and discharge modes, thus facilitating bidirectional power flow for energy balance in the system.
- The interface with the grid is performed using a VSC and an LC filter, which allows controlled power flow from the hybrid system to the grid.
- The control methodology makes sure that the PV generation, energy storage, and grid interface work in coordination to stabilize the voltage level of the DC link and regulate power flow in the system.

The system is modeled to emulate the characteristics of a grid-connected hybrid system for the study of various aspects of power flow and control in the system.

4.13 Summary

This chapter describes the proposed PV-BESS hybrid system design in detail using MATLAB/Simulink. This system has been explained in the context of its functioning and performance in each of the subsystems. The next chapter will analyze the system performance results through various scenarios.

Chapter 5

Results And Analysis

5.1 Introduction

In this chapter, the findings of the dynamic simulations conducted using MATLAB/Simulink for the hybrid photovoltaic and battery energy storage system (PV-BESS) are presented. The performance of the system is evaluated under different irradiation conditions, including the rainy season, summer, winter, and the annual average, to account for the effect of seasonal variation on the hybrid system's performance [13], [19].

The performance evaluation focuses on criteria such as PV power generation, BESS behavior, DC-link voltage regulation, power flow, and grid interaction. Special consideration is devoted to explaining how the hybrid system is able to distribute the load demand among the PV generator, BESS, and the grid [22].

Unlike studies that consider the substitution of traditional generation by renewable energy systems, in this study, the ability of the hybrid PV-BESS system in contributing to load demand and running the system in different operational conditions is studied without claiming that it can substitute traditional generation fully because more work needs to be done to confirm that aspect [2], [6].

5.2 Season 1: Rainy Condition

The rainy condition represents a low irradiance period, where solar energy availability is significantly reduced. This scenario is critical for evaluating the system’s behavior under unfavorable environmental conditions.

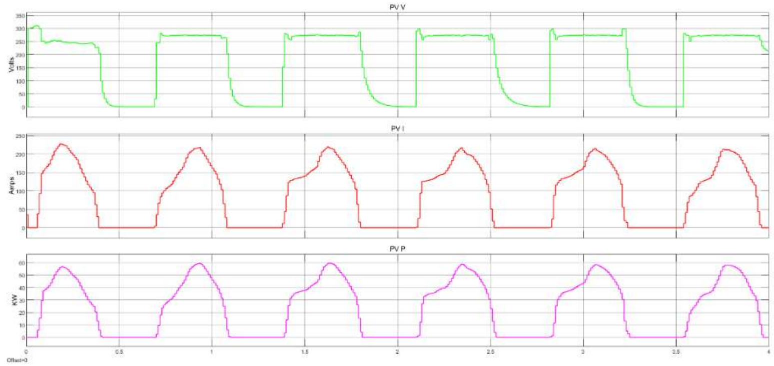


Figure 5.1: PV Output - Rainy Season

The solar panel energy generation pattern is highly variable, and the system produces no energy at night as depicted in F~~f~~igure 5.1. The finding indicates that solar energy production is an unreliable source of energy that necessitates the use of batteries or other means to store the energy generated. In the day, the solar panel produces minimal energy due to low sunlight intensity.

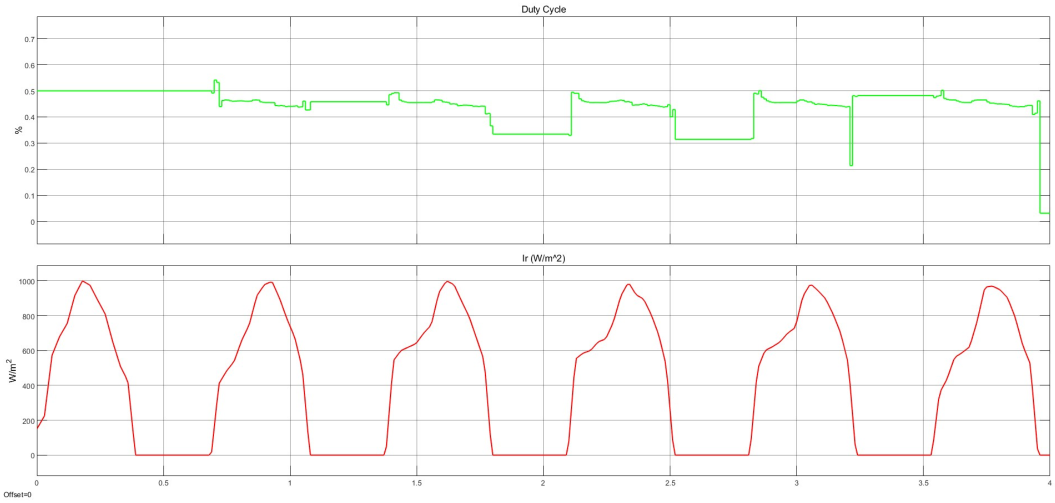


Figure 5.2: MPPT Duty Cycle and Irradiance Profile - Rainy Season

The duty cycle continues to vary with changes in the intensity of light by the MPPT controller as shown in figure 5.2. The varying duty cycle shows the success of the incremental conductance method in tracking the MPP.

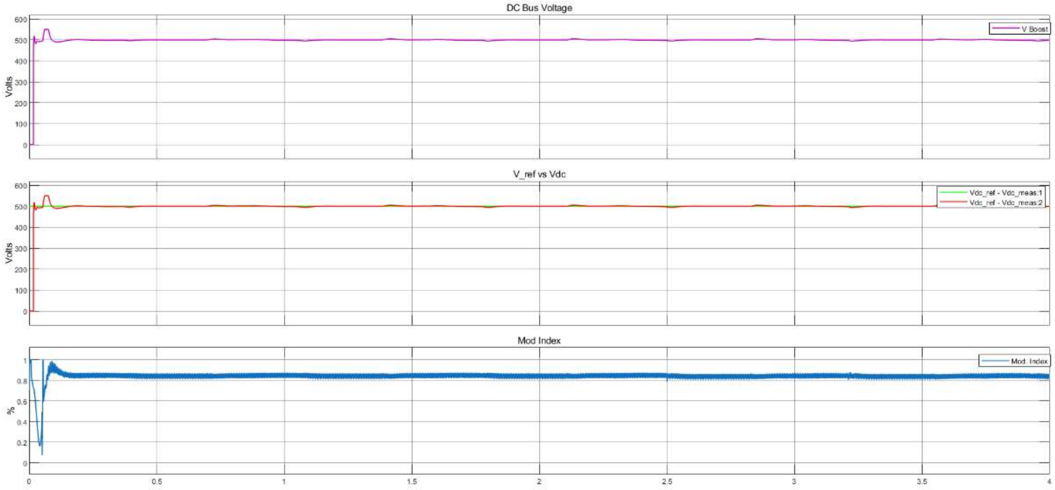


Figure 5.3: Boost Converter Performance - Rainy Season

Figure 5.3 illustrates; DC-link Voltage remains constant at around 500V despite changes in PV power generation. This clearly shows how efficient the boost converter and its control system are in maintaining the DC-link voltage stable, which is necessary for inverter performance.

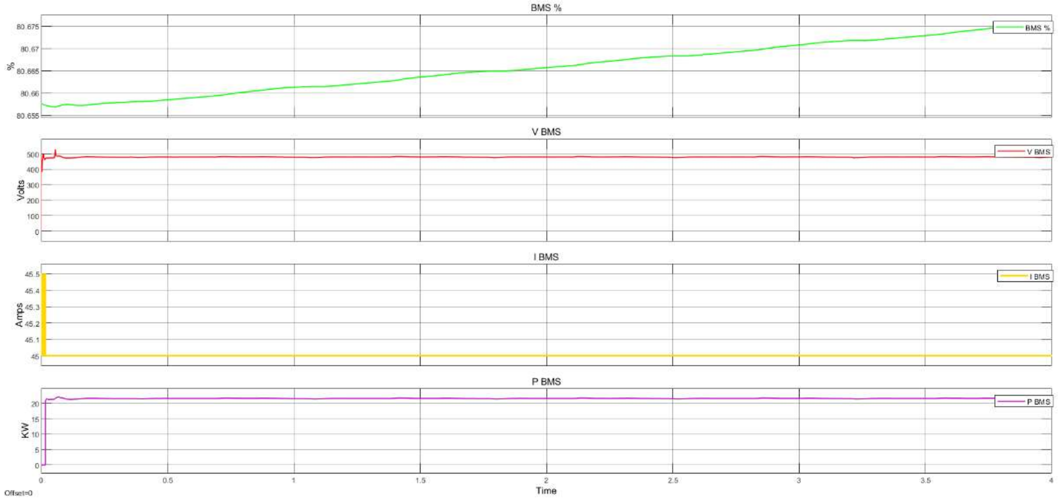


Figure 5.4: Battery Performance (SoC, Voltage, Current, Power) - Rainy Season

The response of the battery under low solar insolation is shown in Figure 5.4. The battery assists in providing extra power to satisfy the load, but the SoC does not show any drastic reduction during the simulation time period. This implies that the battery has not been drained significantly, which is due to two reasons: (a) shorter simulation time period and (b) higher battery capacity compared to load demand. Therefore, the battery undergoes partial discharge and still retains high SoC.

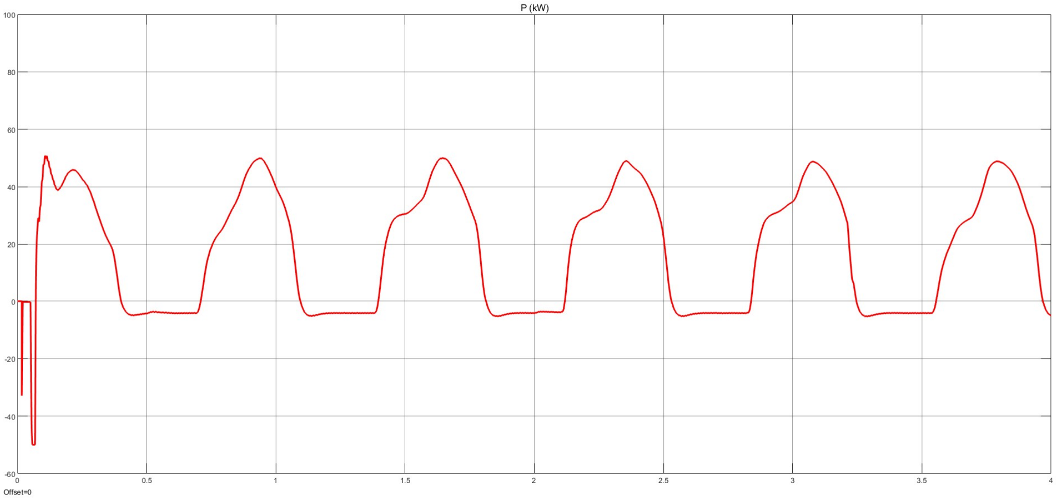


Figure 5.5: Power from Renewable Source (Bus B1) - Rainy Season

Figure 5.5 shows the contributions made by the photovoltaic (PV) cells and batteries at Bus B1. Due to low solar radiation, the energy generated by PV cells remains low and is inadequate to fulfill the load on its own. Batteries make up for this shortfall but still fail to satisfy the load demands.

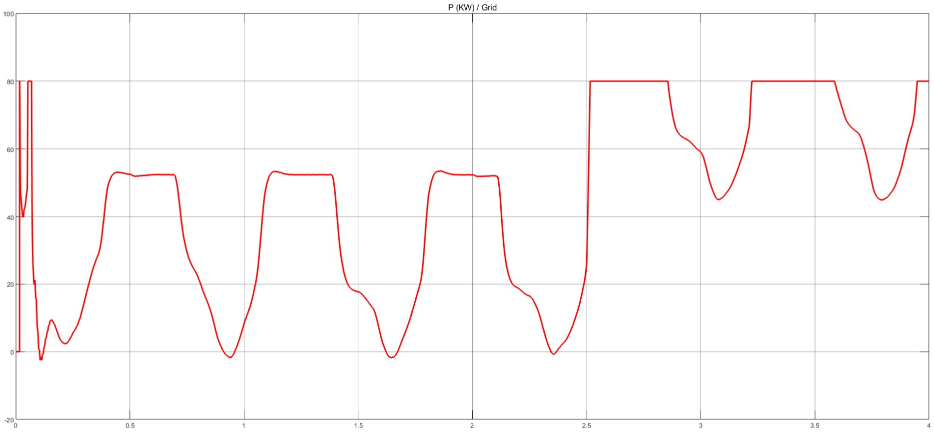


Figure 5.6: Power from Grid (Bus B2) - Rainy Season

Figure 5.6 shows how much the grid contributes to the total load. This observation is consistent with the fact that, with reduced irradiation, the system needs a considerable amount of input from outside sources to keep the balance of power. The extent of the grid's contribution is explained by the limited capacity for renewables.

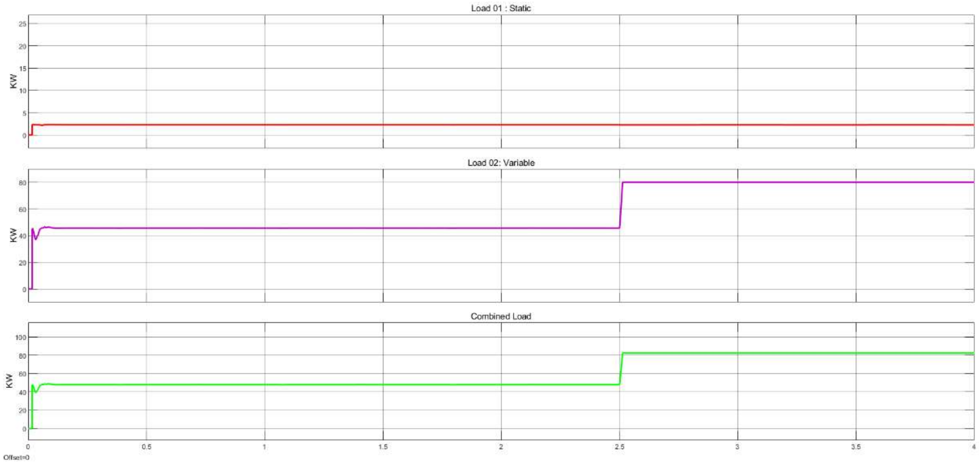


Figure 5.7: Total Power Distribution (Active, Dynamic, Combined) - Rainy Season

The total power balance between the PV array, batteries, and the grid is shown in Figure 5.7. The load requirement is satisfied by balancing all the components. Since the grid contributes significantly and there is minimal battery discharging, it shows that the energy management focuses on stabilizing the system rather than discharging the batteries completely. It also suggests that the battery is neither sized nor controlled to provide complete load satisfaction.

5.3 Season 2: Summer Condition

In situations with high irradiation values, as seen in the summer case, the output power of the PV system reaches its maximum value.

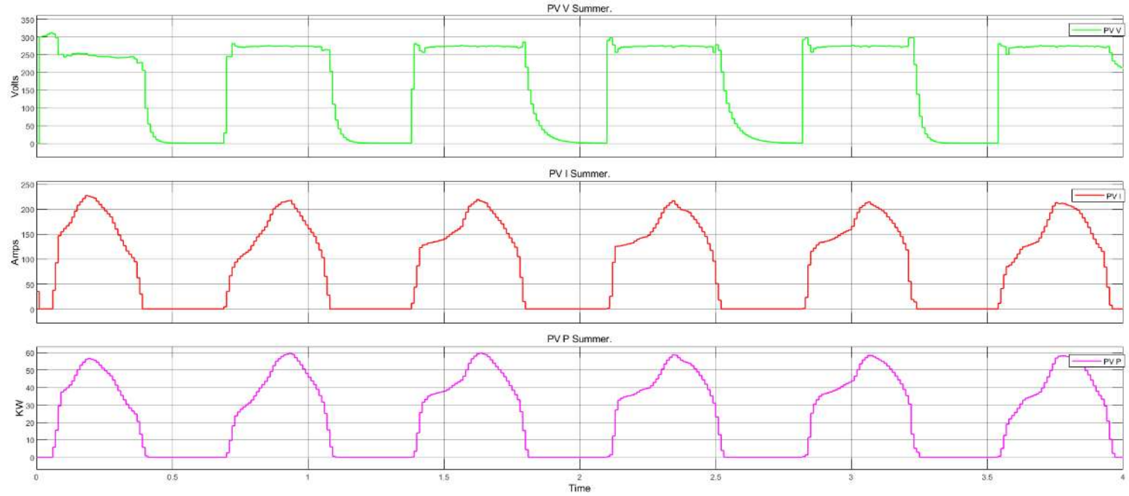


Figure 5.8: PV Output - Summer Season

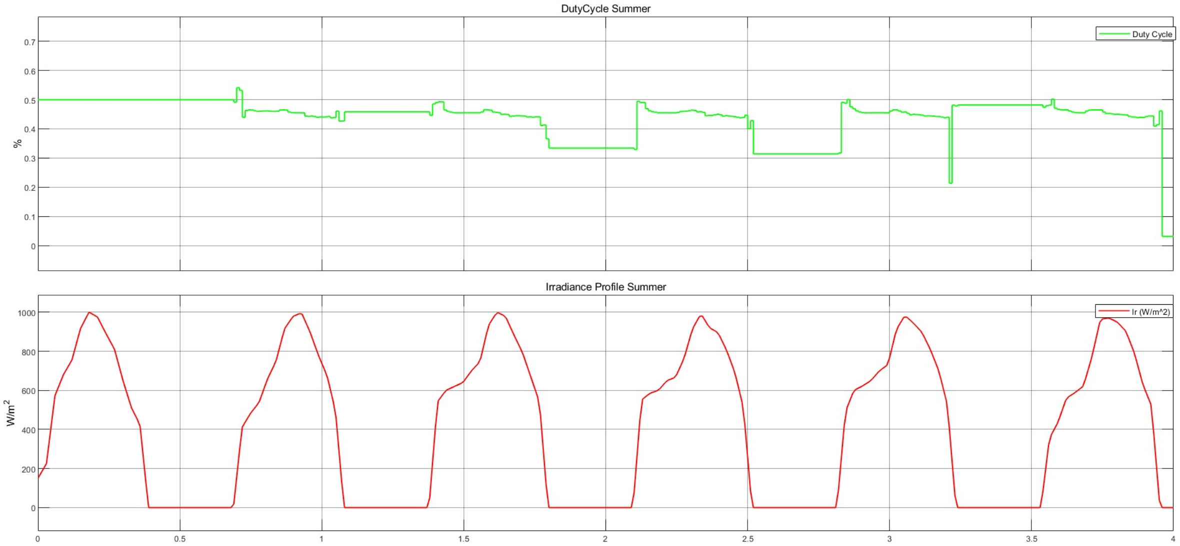


Figure 5.9: MPPT Duty Cycle and Irradiance Profile - Summer Season

Figure 5.8 and Figure 5.9 clearly show that the photovoltaic system runs at its maximum efficiency, and the MPPT control system maintains the efficiency of the system. The constant duty cycle shows stability of operation without any changes.

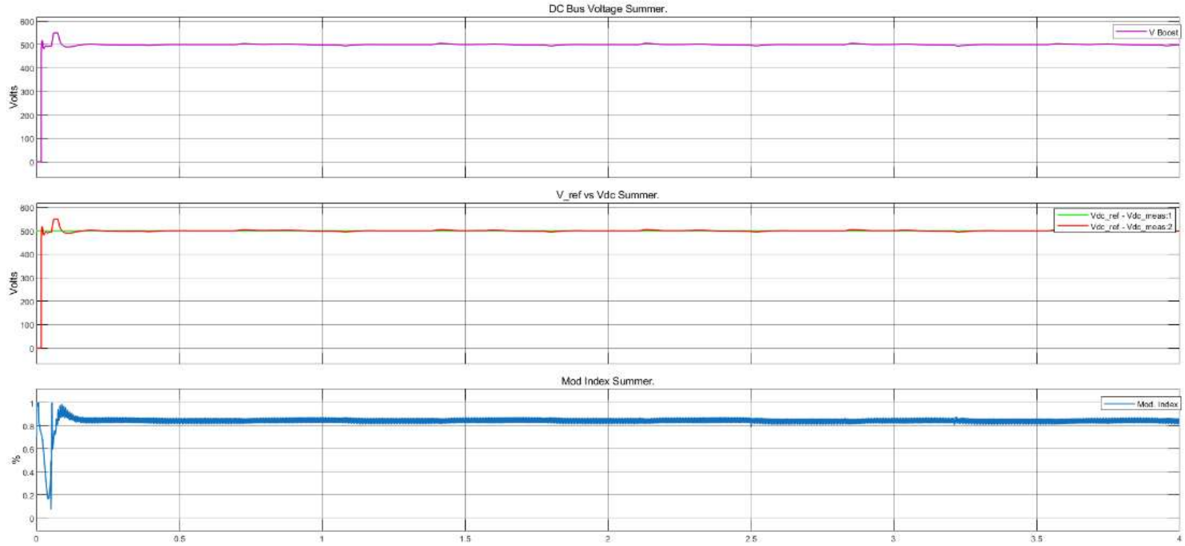


Figure 5.10: Boost Converter Performance - Summer Season

The boost converter maintains a stable DC-link voltage, ensuring efficient power transfer from the PV system to the DC bus.

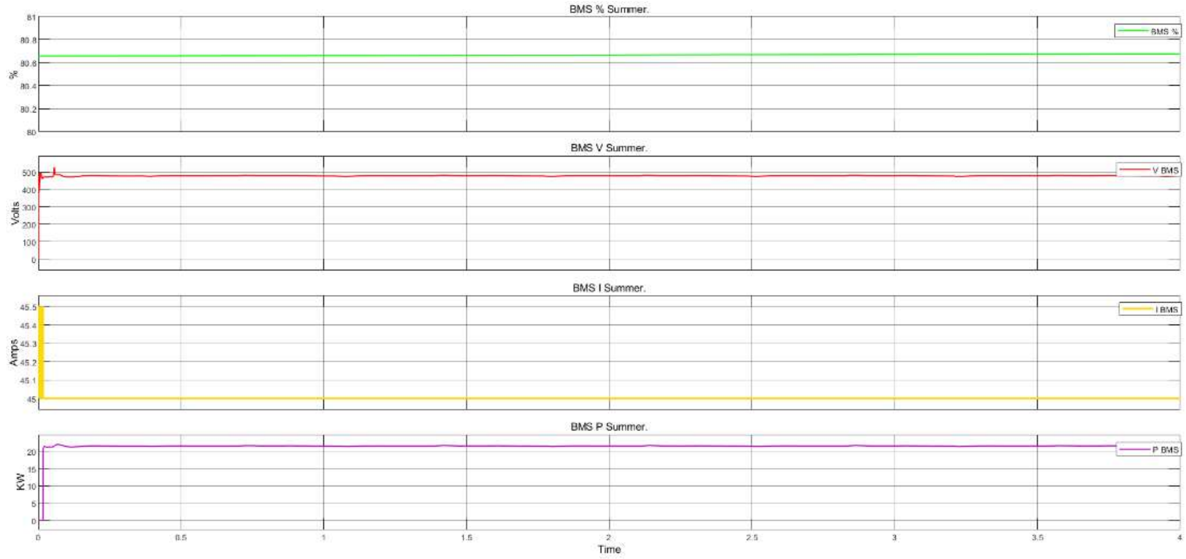


Figure 5.11: Battery Performance (SoC, Voltage, Current, Power) - Summer Season

It is clear from Figure 5.11 that the battery works mostly under the charging operation mode. An increase in the SoC level shows that there is an extra amount of PV energy available for storage. But it seems that there isn't any significant discharge process because the demand load doesn't utilize the energy stored in the battery.

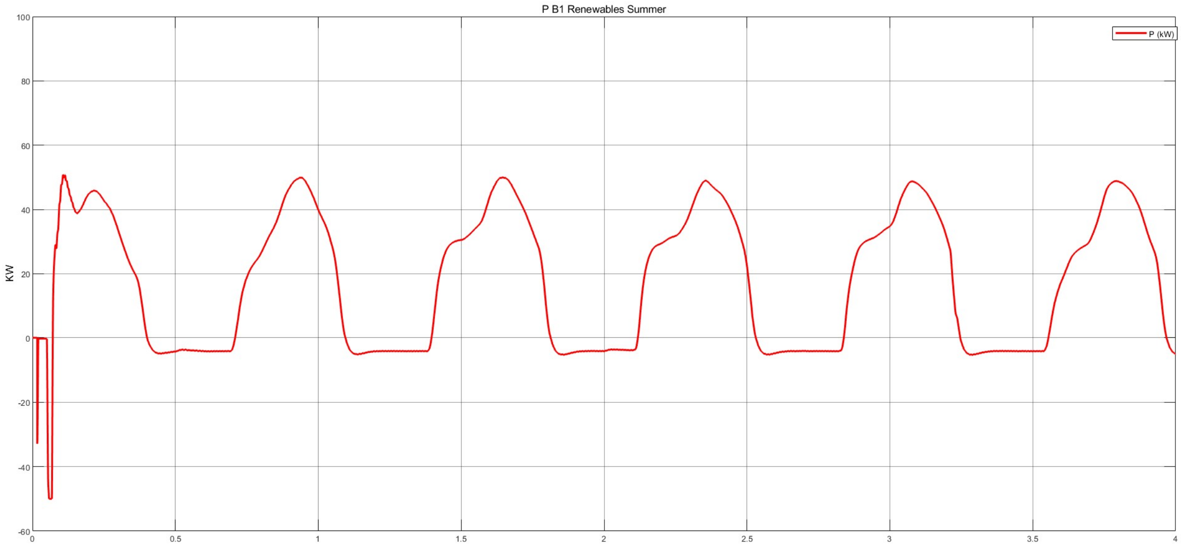


Figure 5.12: Power from Renewable Source (Bus B1) - Summer Season

Figure 5.12 shows how photovoltaic (PV) generation satisfies most of the load requirement, and the battery acts only as a storage medium without discharging.

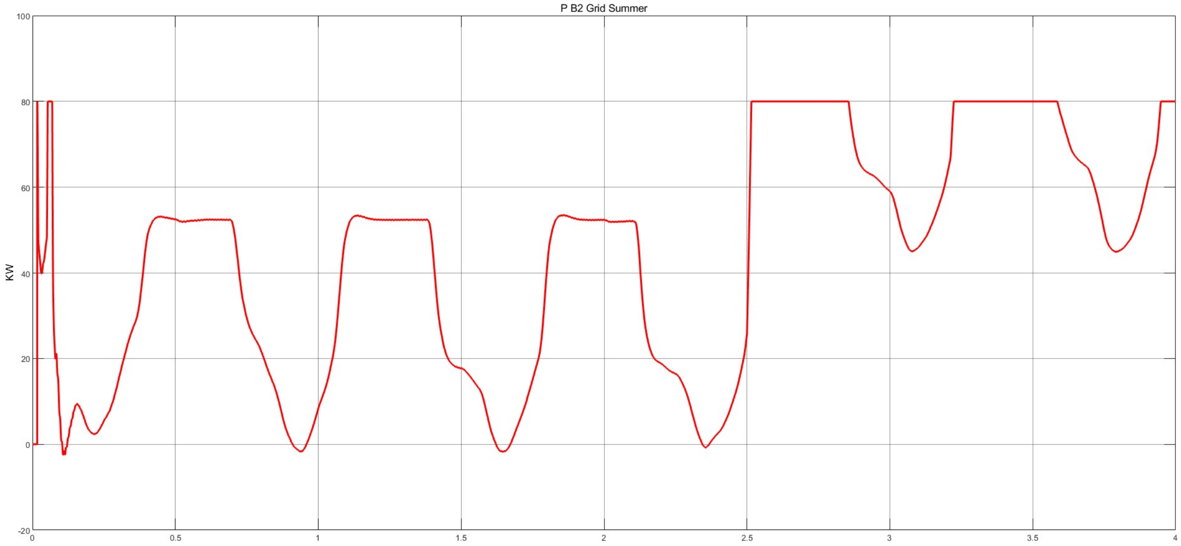


Figure 5.13: Power from Grid (Bus B2) - Summer Season

Figure 5.13 shows low input from the grid due to lower dependence on external sources when there is higher solar irradiation.

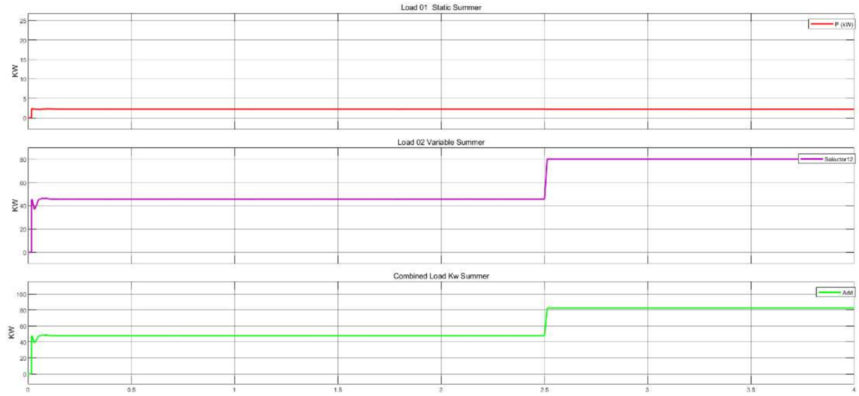


Figure 5.14: Total Power Distribution (Active, Dynamic, Combined) - Summer Season

Figure 5.14 clearly shows that the system works mainly through PV generation, and the surplus energy is used for charging the battery. The small utilization of the battery shows that the simulation may not cover the complete daily cycle.

5.4 Season 3: Winter Condition

This case reflects the moderate irradiance environment, where there is limited sunlight and shorter daylight compared to the summer case. This case is very important for evaluating the performance of the system if the availability of renewable energy is only partially limited.

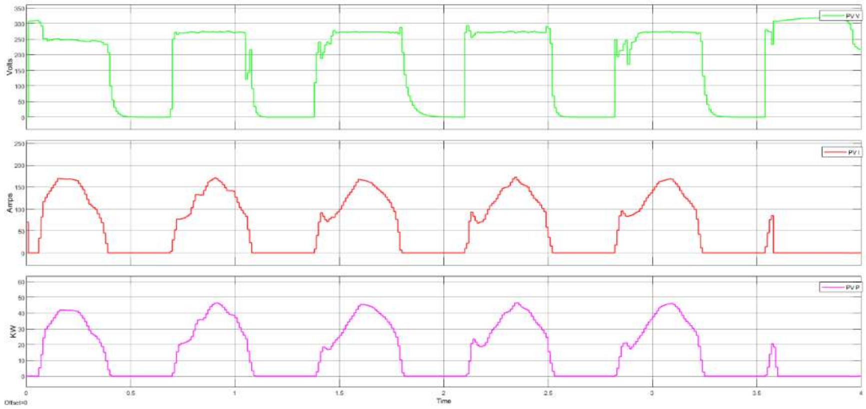


Figure 5.15: PV Output Characteristics (Voltage, Current, Power) - Winter Season

Figure 5.15 represents the photovoltaic (PV) voltage, current, and output power based on winter irradiance conditions. Compared to the previous one (summer), there is less PV output due to the lower amount of received energy from solar panels. However, it is worth noting that the output is rather stable and does not oscillate sharply, meaning that the PV panel system is working efficiently. The lower current is responsible for this behavior, whereas the voltage is more stable due to the specific nature of PV systems.

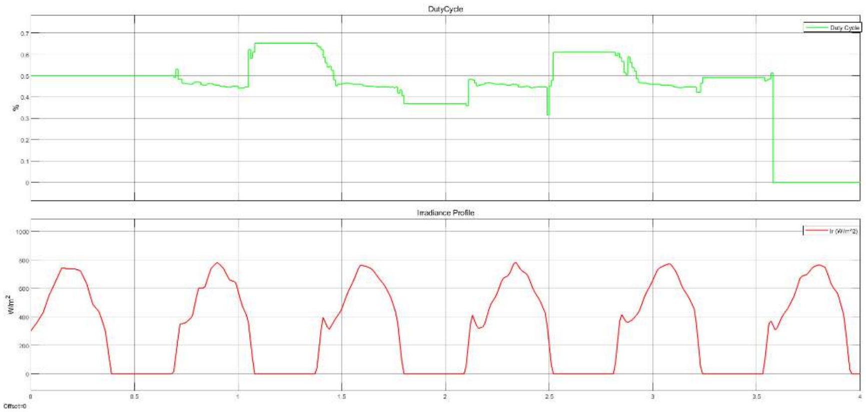


Figure 5.16: MPPT Duty Cycle and Irradiance Profile - Winter Season

Figure 5.16 describes the irradiance change together with the MPPT duty cycle. In accordance with the case described above, it can be seen that the MPPT controller regulates the duty cycle according to the changing irradiance. It can be noted that the variation in the duty cycle becomes smoother than in extreme cases (e.g., sharp irradiance change). This means that the MPPT controller works effectively in the stable area of operation.

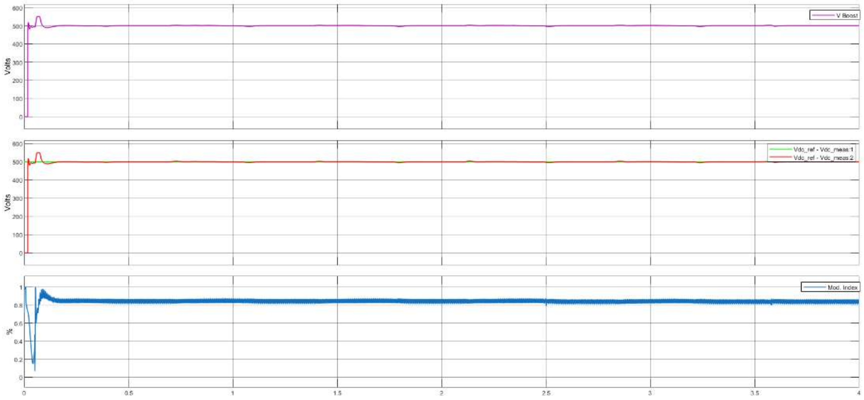


Figure 5.17: Boost Converter Performance (Vdc, Reference, Modulation Index) - Winter Season

Figure 5.17 demonstrates the variation in the DC-link voltage (Vdc) and the reference one, along with the converter's modulation index. As one can see from the chart, the DC link voltage is regulated successfully because it does not differ from the reference voltage. Although there was less energy received from the source, the converter operated stably due to the modulation index adjustment.

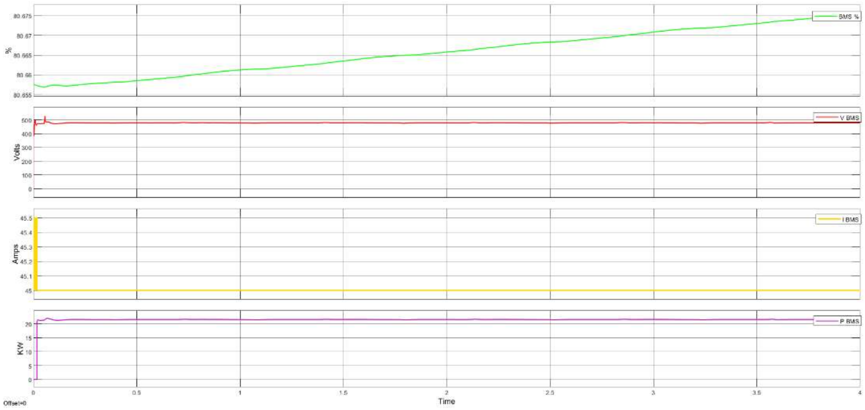


Figure 5.18: Battery Performance (SoC, Voltage, Current, Power) - Winter Season

Figure 5.18 shows the battery characteristics based on SoC, voltage, current, and power. The battery is seen to undergo both charging and discharging actions because it acts as the balancing element to reconcile the differences in generation and loads. Whenever there is an excess in the generation compared to the load requirements, the battery starts charging, while when there is a deficit, it discharges.

However, the SoC varies slightly, indicating that there is no complete battery cycling due to the small differences between generations and loads. This is attributed to the short simulation period. In this regard, the battery acts more as an energy buffer than a store of energy for long periods of time.

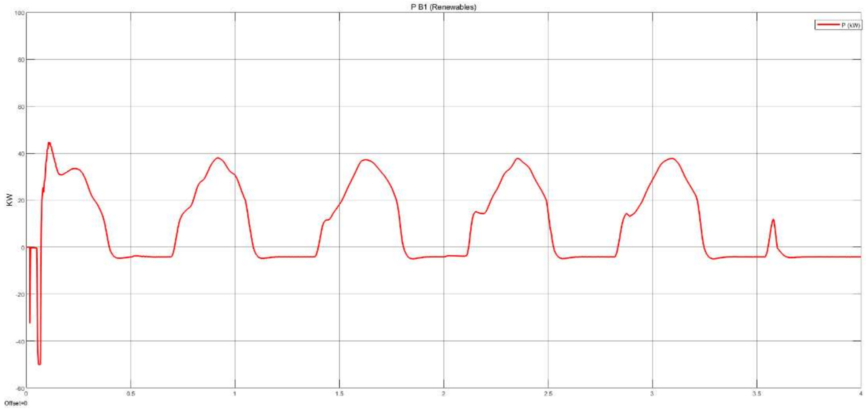


Figure 5.19: Power from Renewable Source (Bus B1) - Winter Season

The power contribution from renewables to Bus B1 is illustrated in Figure 5.19. The power contribution from the renewable sources is adequate for a portion of the load, although it does not always cover the required demand. Power contributions from renewable sources depend on both photovoltaic generation and battery assistance.

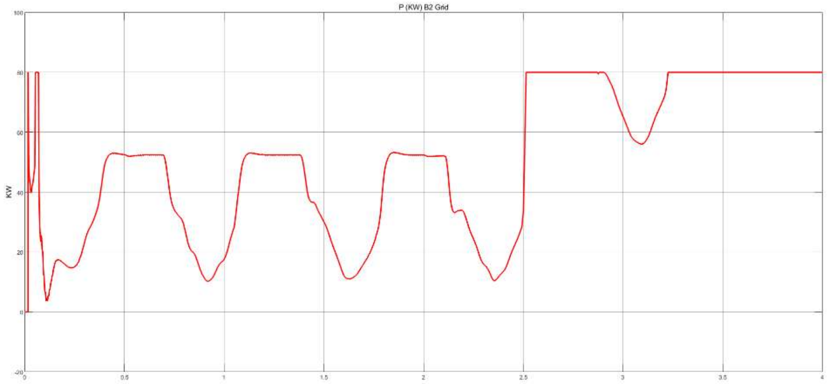


Figure 5.20: Power from Grid (Bus B2) - Winter Season

Power contributed from the grid is shown in Figure 5.20. Power contribution from the grid continues to be modest during the entire simulation. This implies that there is a requirement for grid assistance during hybrid operation due to inadequate power generation from PV and the battery. This result proves that the system can only work with grid help when irradiance is at moderate levels.

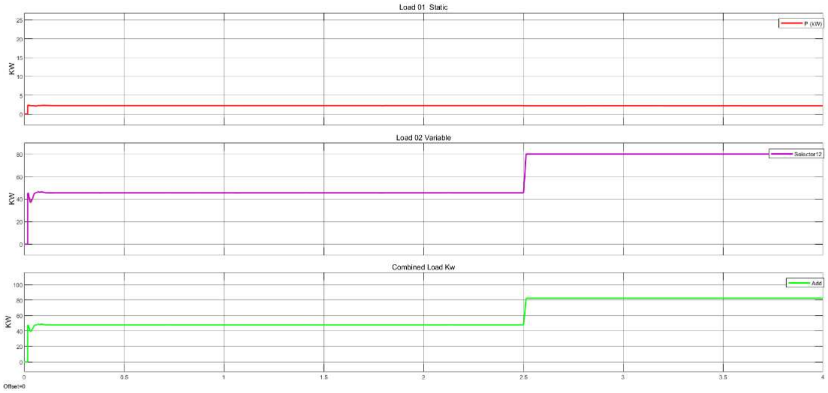


Figure 5.21: Total Power Distribution - Winter Season

Figure 5.21 shows the balance between PV power, battery power, and grid power for hybrid operation. All three contributions provide sufficient load demand with their balance. The relatively even distribution of power indicates that this simulation runs in the intermediate conditions for winter. Neither PV dominates during winter simulation, and there is not heavy dependence on the grid as in rainy conditions.

5.5 Season 4: Annual Average Condition

This particular case study represents a plausible long-term simulation based on average irradiation data (704 W/m²).

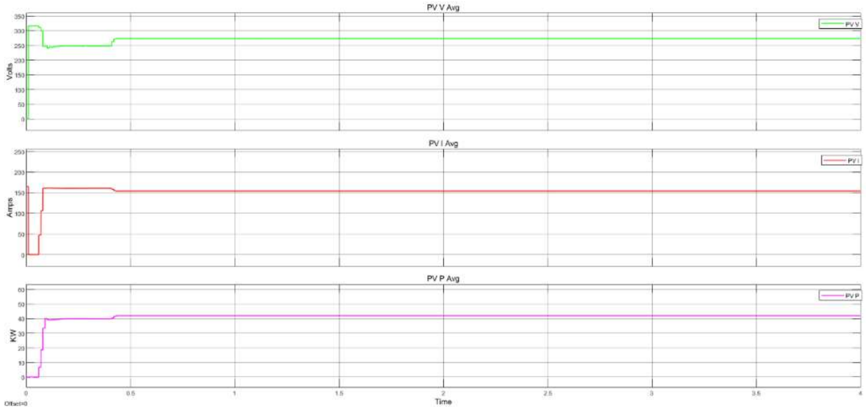


Figure 5.22: PV Output Characteristics (Voltage, Current, Power) - Average Condition

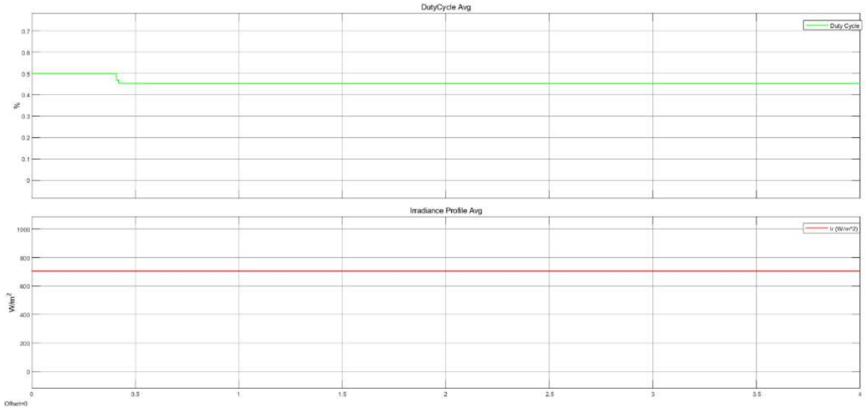


Figure 5.23: MPPT Duty Cycle and Irradiance Profile - Average Condition

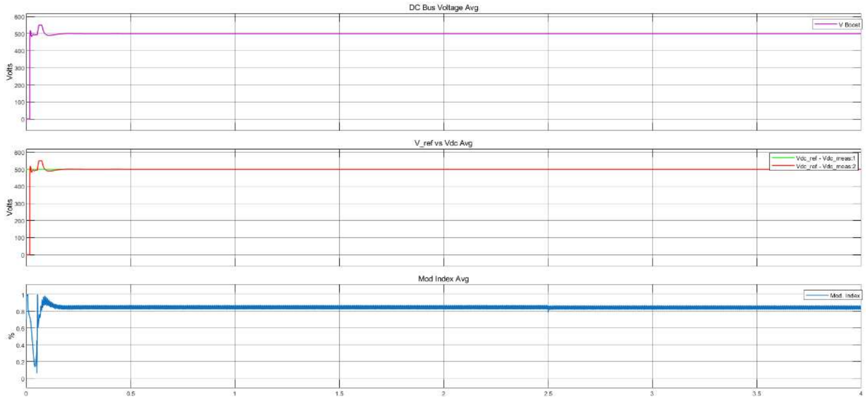


Figure 5.24: Boost Converter Performance (Vdc, Reference, Modulation Index) - Average Condition

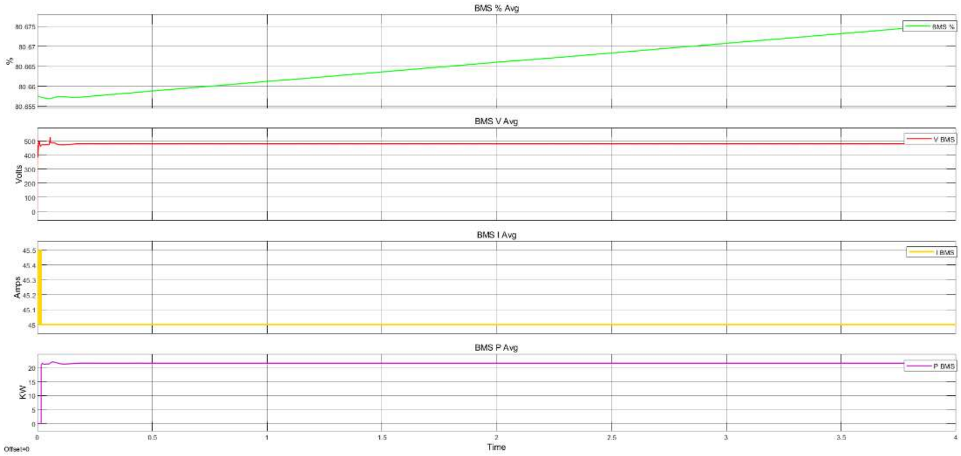


Figure 5.25: Battery Performance (SoC, Voltage, Current, Power) - Average Condition

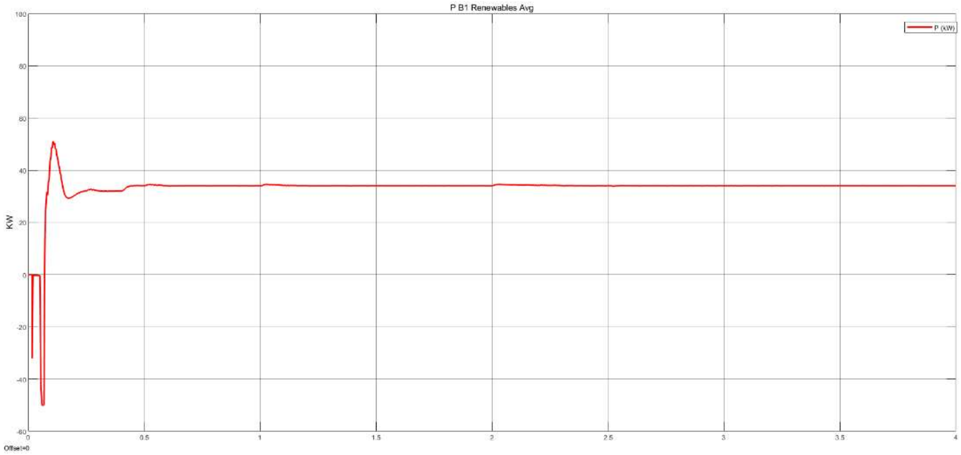


Figure 5.26: Power from Renewable Source (Bus B1) - Average Scenario

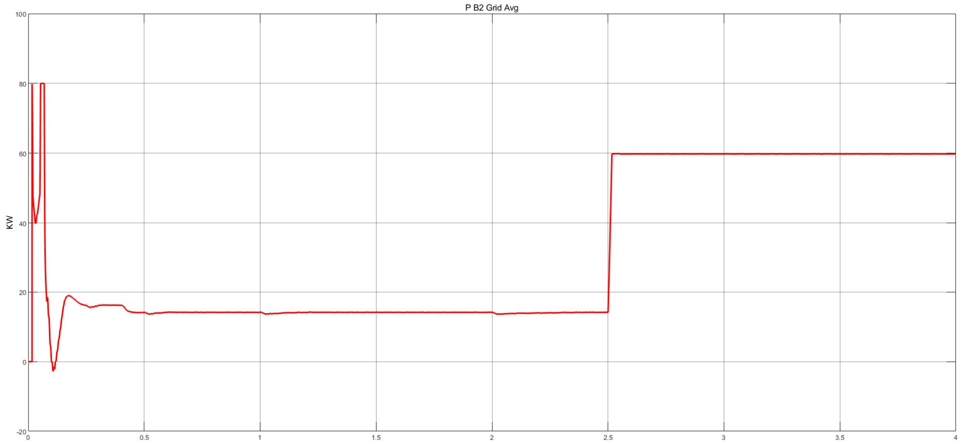


Figure 5.27: Power from Grid (Bus B2) - Average Condition

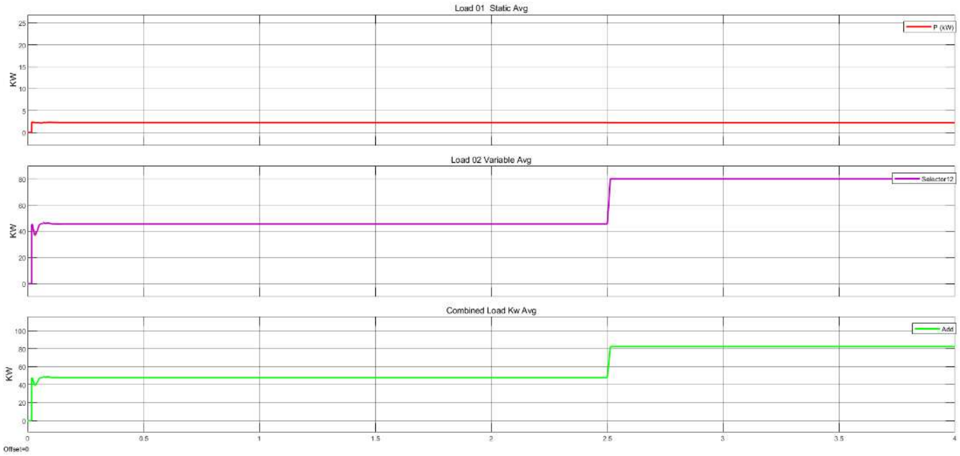


Figure 5.28: Total Power Distribution - Average Condition

The outcomes reveal that the system operates in a well-balanced regime. The photovoltaic source provides a considerable part of the load, whereas the battery stabilizes the short-term variations, and the grid covers the rest of the load. The limited fluctuations in the state of charge of the battery show that the model primarily reflects the short-term behavior of the system.

Table 5.1: Season Comparison

Scenario	***PV Output***	***Battery Use***	***Grid Use***	***Stability***
Rainy	Low	High	High	Stable
Summer	High	Charging	Low	Excellent
Winter	Moderate	Moderate	Moderate	Stable
Annual	Balanced	Balanced	Low	Stable

5.6 State of Charge (SOC) Behavior:

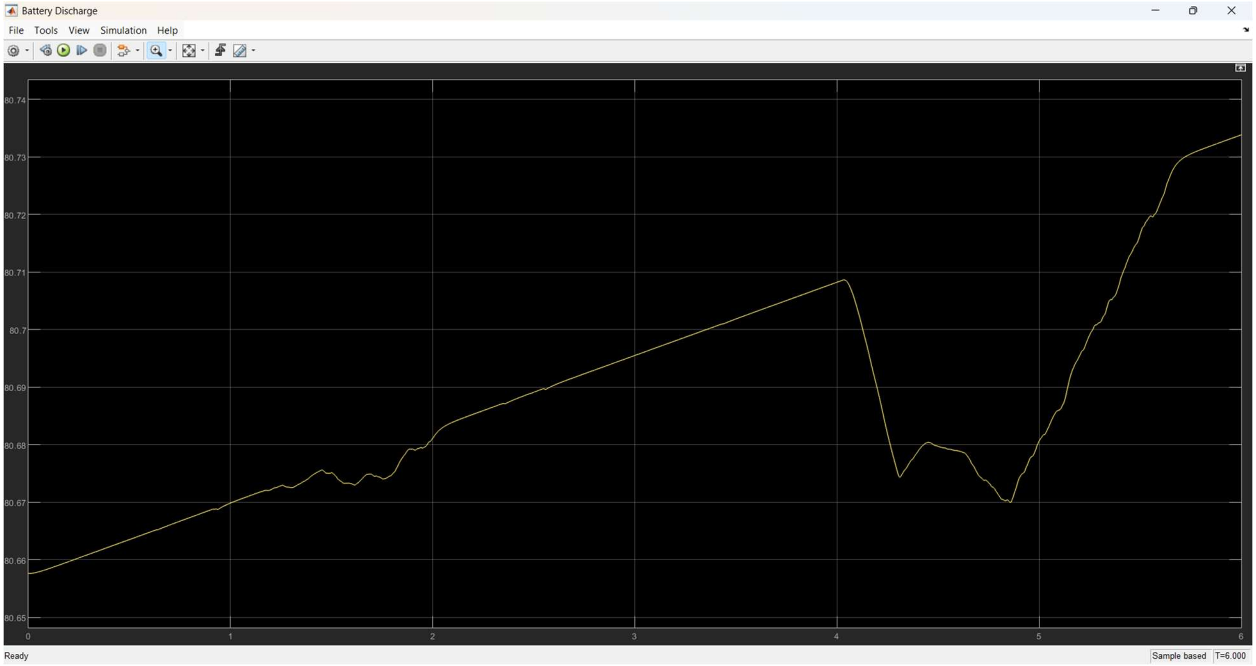


Figure 5.29: State of Charge (SOC) Behavior (Simulation run time is 6s)

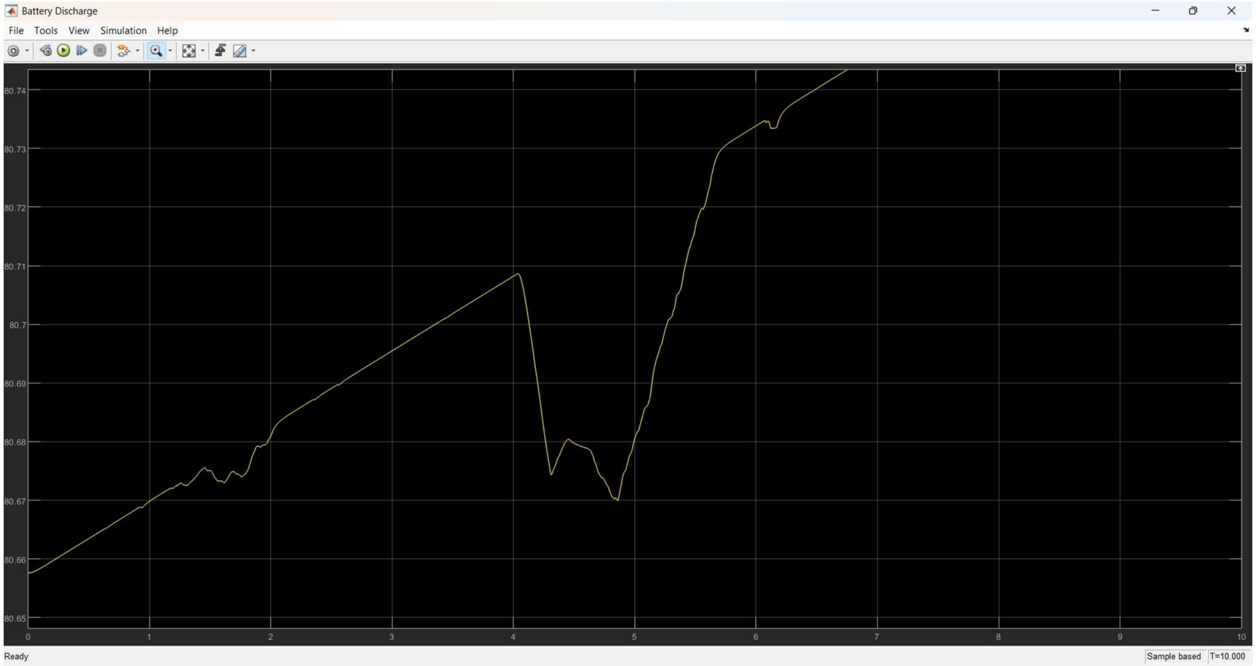


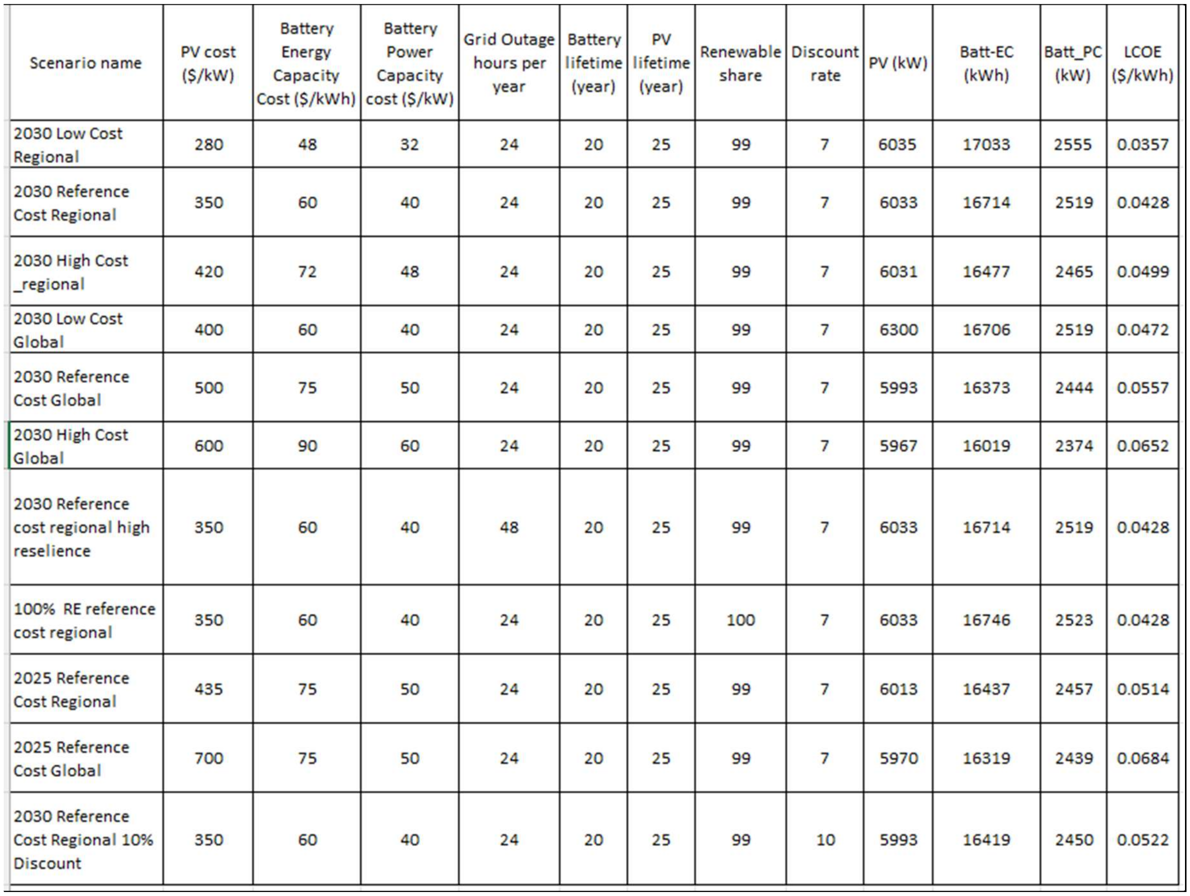
Figure 5.30: State of Charge (SOC) Behavior (Simulation run time is 10s)

The state-of-charge (SOC) behavior of the battery was evaluated by means of continuing the hybrid-PV battery output for two simulations run times 6s and 10s, to observe the short-term dynamic response under different PV and load conditions. In each case, the SOC profile remained within the SOC band (≈80.65–80.74%). During periods of increasing PV generation, the SOC increases steadily as excess solar power changes the battery, while a reduction of PV generation or an increase in load profile will cause the corresponding SOC to decrease as the battery discharges. The above two graphs show control behavior, with the battery performance grid-support mode smoothing fluctuations, maintaining operational activities, and avoiding large depth-of-discharge excursions.

5. 7 REopt Scenario Analysis

Table 5.2 shows the LCOE in whole exclusive scenarios, which shows that up to 99% (almost full) of the energy supplied through 3 fossil fuel generators can be converted through a solar PV–battery hybrid system at an aggressive tariff. The LCOE is remarkably tactile for production costs and device parameters, starting from 0.0357 to 0.0652 USD/kWh; Decreasing values correspond to reduced cost events, while higher values replicate higher cost estimates. Importantly, all cases stand far below the present average electricity tariff in Bangladesh (0.11 USD/kWh), confirming the economic feasibility. The life cycle valuation (LCC) based on the LCOE impact likewise shows the strong financial blessing of the hybrid gadget over the fossil-gas reference case. The highest savings (4.16 million USD) result from lower capital costs and optimized scale within the lower price 2030 local scenario, while lower savings are set in the high cost global in 2030 due to higher prices and less favorable conditions.

Table 5.2: Comparative Summary of REopt Optimization Scenarios



Scenario name	PV cost ($/kW)	Battery Energy Capacity Cost ($/kWh)	Battery Power Capacity cost ($/kW)	Grid Outage hours per year	Battery lifetime (year)	PV lifetime (year)	Renewable share	Discount rate	PV (kW)	Batt-EC (kWh)	Batt_PC (kW)	LCOE ($/kWh)
2030 Low Cost Regional	280	48	32	24	20	25	99	7	6035	17033	2555	0.0357
2030 Reference Cost Regional	350	60	40	24	20	25	99	7	6033	16714	2519	0.0428
2030 High Cost _regional	420	72	48	24	20	25	99	7	6031	16477	2465	0.0499
2030 Low Cost Global	400	60	40	24	20	25	99	7	6300	16706	2519	0.0472
2030 Reference Cost Global	500	75	50	24	20	25	99	7	5993	16373	2444	0.0557
2030 High Cost Global	600	90	60	24	20	25	99	7	5967	16019	2374	0.0652
2030 Reference cost regional high reselience	350	60	40	48	20	25	99	7	6033	16714	2519	0.0428
100% RE reference cost regional	350	60	40	24	20	25	100	7	6033	16746	2523	0.0428
2025 Reference Cost Regional	435	75	50	24	20	25	99	7	6013	16437	2457	0.0514
2025 Reference Cost Global	700	75	50	24	20	25	99	7	5970	16319	2439	0.0684
2030 Reference Cost Regional 10% Discount	350	60	40	24	20	25	99	10	5993	16419	2450	0.0522

In all cases, the optimization results show high penetration of renewable energy with large to almost complete reduction of grid dependence. In contrast to the examples, battery storage consistently improves the overall performance of the system through increased renewable energy consumption, reduced grid loads, and increased operational stability under variable aging conditions.

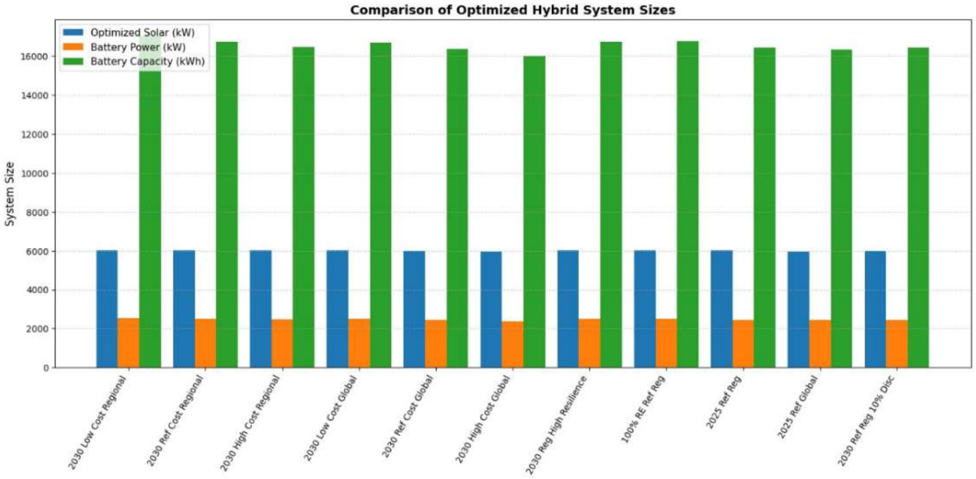


Figure 5.31. Optimized sizes of photovoltaics and battery systems within REopt scenarios

This graph shows the optimized size of photovoltaic (PV) array installation, power capacity of batteries, and energy storage capability of batteries in eleven REopt scenarios considered in this research paper. The blue bars correspond to the installed PV capacity (kW), while the orange bars represent the battery power capacity (kW). In turn, the green bars represent battery energy storage capacity (kWh). As can be seen from the analysis of the obtained results, despite some differences in projections regarding costs and regional conditions for renewable energy technologies deployment, there is relatively strong consistency in the optimized sizes of PV installations and battery power/energy storage. Such a result indicates a stable system sizing performance in case of changes in economic assumptions and the possibility to implement a scalable photovoltaic-battery energy system to replace conventional fossil fuel energy generation sources.

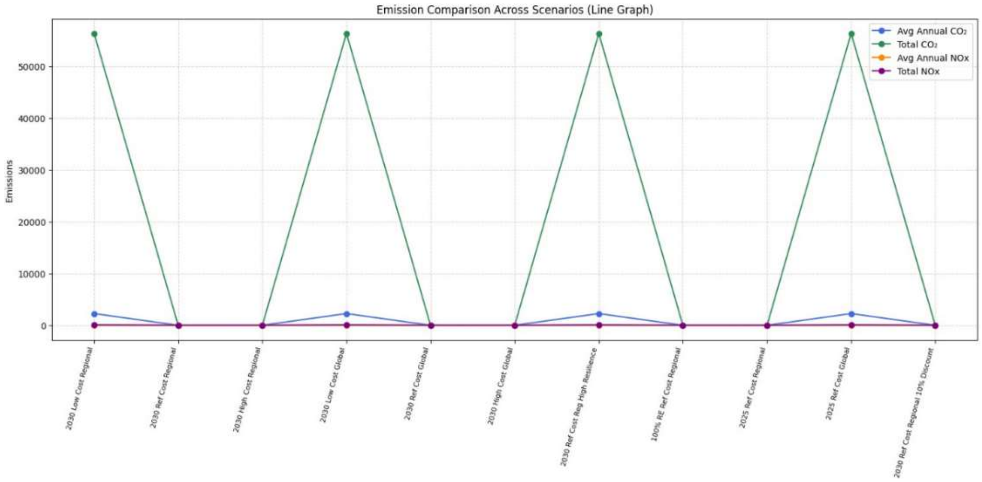


Figure 5.32. Annual and cumulative CO_2 and NO_x emissions comparison for REopt scenarios

This graph shows the annual and cumulative emissions of CO_2 and NO_x in tons per year and ton-years, respectively, for the eleven REopt scenarios considered in the current paper. Metrics were assessed to identify the positive effect on the environment caused by shifting from traditional electricity generation through fossil fuels towards optimized photovoltaic generation with BESS configurations. As seen in the figure 5.31, a considerable decrease in both CO_2 and NO_x emissions occurs when the use of renewable energy is considered. The greatest emission cuts were noted in scenarios involving higher dependence on the use of PVs and BESS. Such results highlight the environmental benefits of using large-scale solar-powered energy systems. On a policy and sustainability level, the presented findings confirm that switching from new or outdated fossil fuel-fired generation technologies towards optimized solar-plus-storage systems results in a significant reduction of greenhouse gas emissions, as well as local air pollution. In the context of rising electricity consumption and growing concern over environmental issues, such systems could be beneficial in terms of their future implementation in Bangladesh.

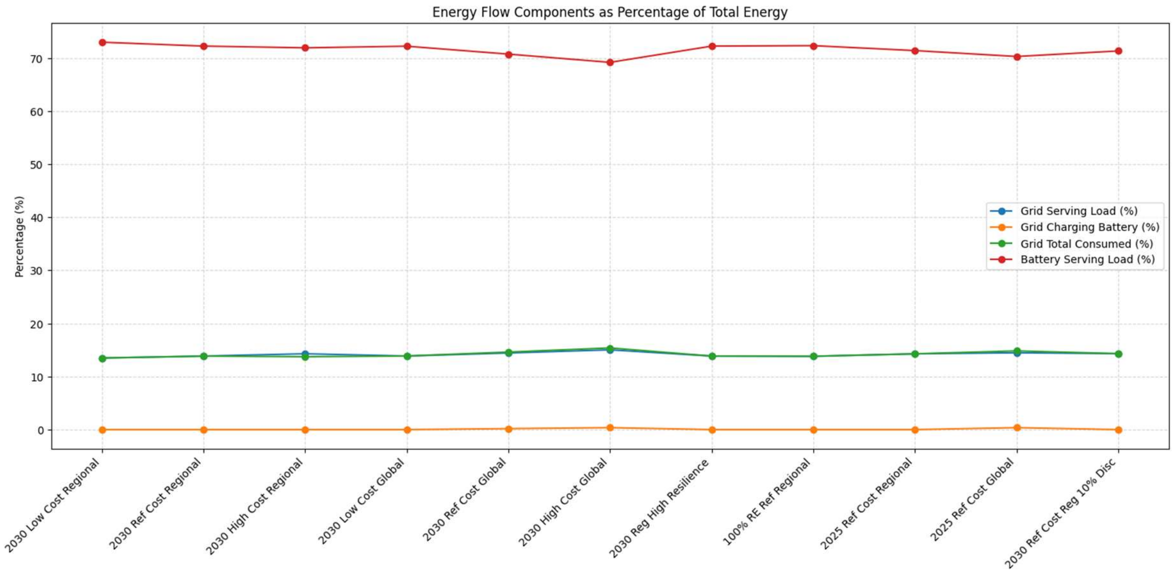


Figure 5.33. Energy Flow components for the PV-BESS System in REopt Scenarios

The graph shows the relative contribution of the four major electricity transfers with current ties in several techno-economic conditions. The battery service load, around 70–73%, remains the primary supply aggregation need in all scenarios, demonstrating the centrality of battery maintenance to maintain equipment reliability. In comparison, the grid's total consumption and serving load contributions are much lower, around 13–15% and barely below that, respectively, indicating limited reliance on direct network imports. Grid charging batteries remain low at 0–2%, confirming that batteries are hardly ever charged from the grid and primarily rely on renewable energy as an alternative. Together, these trends reveal a device optimized for excessive self-consumption.

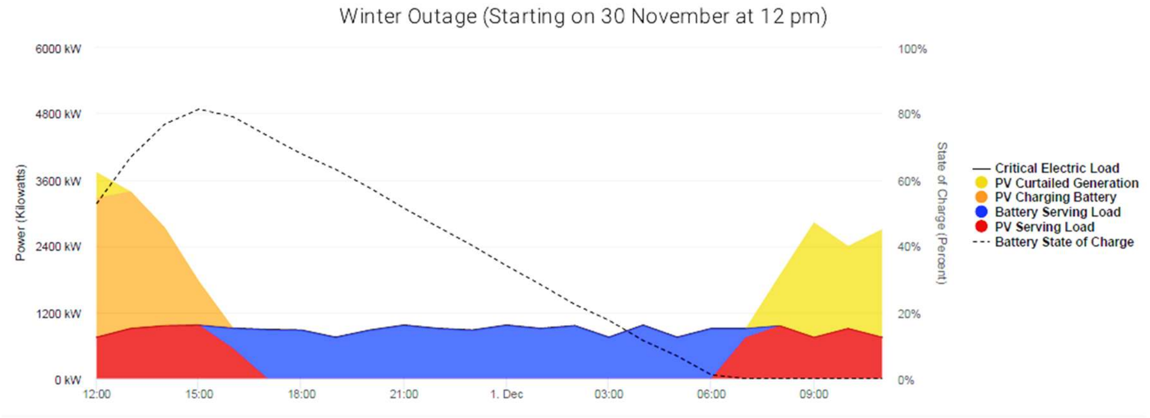


Figure 5.34. Operational characteristics of REopt simulation for optimized PV-BESS energy storage during an outage event in winter

This is a representative dispatch of the REopt analysis of the PV-battery energy storage system that was performed. The dispatch profile is represented here as being representative since the operation characteristics remained constant for all eleven possible scenarios for costs and deployments.

The dispatch shows how the solar generation is used to cover the load, how the excess generation is stored in the battery, and how the critical loads are supplied from battery energy during the outage period. For example, in the early hours of the morning, when the sun rises, the PV generation covers the electrical load, storing excess in the battery energy storage system. In the late hours, when PV generation ends, and during the night-time, the stored battery energy is used, thereby slowly depleting the SoC of the storage. With the morning hours, again the generation starts covering the load, bringing the system back into balance.

The dispatch of the optimized PV-battery storage system confirms the viability of its implementation as an alternative solution to generating electricity using fossil fuels during grid outage events. Thus, in view of the results obtained, the viability of large-scale PV-battery installations can be confirmed, especially in those regions where the energy generated by such installations can be substituted for existing or planned fossil fuel power plants, such as Bangladesh.

5.8 Key Findings

The simulation outcomes obtained via the MATLAB/Simulink modeling enable assessing the performance of the proposed hybrid PV-BESS power supply system subjected to various conditions of irradiance and dynamic load. For this purpose, four exemplary cases are considered: rainy season, summer season, winter season, and annual average [13].

As a result of calculations, it has been concluded that the power balance is achieved, and load demands are met in all four cases. However, it should be noted that balancing load and maintaining power balance is achieved not by using the proposed PV-BESS subsystem solely, but by using its combination with the grid. In addition, the share of the contributions of PV, BESS, and the grid to power generation depends significantly on irradiance conditions.

The battery energy storage system (BESS) serves as an energy buffer that helps achieve power balance by filling the gap between generation and demand [16]. As seen from the simulation outcomes, the state of charge of the battery (SoC) is rather high in all scenarios. Thus, it appears that the battery cannot fulfill its function since there are no deep discharges, which means that the grid supports additional consumption.

Under high irradiance conditions, which can be demonstrated by the case of the summer scenario, the battery works mostly in the charge mode due to excessive PV generation. At the same time, the absence of deep discharges also implies that the battery does not operate intensively and functions mainly as a short-term energy buffer.

Thus, the presence of the grid is crucial because it not only assists the system in cases when there are insufficient amounts of generation but also serves as an alternative energy supplier [2]. This is confirmed by the fact that the contribution of the grid is high even in several cases, including rainy and winter seasons. Therefore, this hybrid power system may be considered as a grid-interactive system.

It is also worth mentioning that the voltage levels have remained stable in all cases, despite dynamic loading and step changes in the applied load. Specifically, the load profile is step-shaped with gradual changes within 2.5 seconds, during which the power goes up from 50 kW to 100 kW. The regulation of the DC-link and total system voltage has also been satisfactory.

5.9 Answer to Core Research Question

It should be highlighted that one of the key objectives of this research is to evaluate whether the proposed PV-BESS could be considered an alternative for fossil fuel-based power plants concerning their performance parameters. It appears that such a PV-BESS system could perform the following key functions: provide active power; provide reactive power due to VSC; and operate with load changes dynamically [15].

Nevertheless, the outcomes of the analysis suggest that the complete replacement of traditional power plants has not been reached at the moment. Though the analyzed PV-BESS can provide the required level of energy generation, it does so by the joint effort of PV, battery, and grid. At the same time, in various cases, especially with low to moderate solar radiation, there is a significant supply of demand from the grid, while the battery capacity is not used completely due to its partial discharge.

In addition, the analyzed hybrid PV-BESS system performs stably under the step increasing load from 50 kW to 100 kW. Furthermore, the battery plays a role in short-term balancing [19], [22].

Hence, on the whole, the system has proved that it could act as an alternative for fossil fuel-based electricity generation; yet, in its current form, it remains grid-assisted generation.

5.10 Summary

In this chapter, the dynamic performance of the PV-BESS hybrid system in four typical irradiance profiles, namely rainy, summer, winter, and average irradiation profiles throughout the year, is examined. In conclusion, the results show that it is possible to operate the system in a stable condition and supply energy demand by the joint effect of PV systems, batteries, and the grid.

System performance varies greatly depending on irradiation conditions. The more moderate the irradiation, the more the performance depends on the grid. While batteries provide short-term power balance, their usage is constrained within the simulation period because of the limitations of the REopt software.

Therefore, the results presented above should not be interpreted as a comprehensive analysis of system operation without the grid, since they mainly demonstrate system stability and energy balance.

These conclusions lay the groundwork for the techno-economic study using the REopt program, which follows the current research.

Chapter 6

Discussion

6.1 Introduction

In this chapter, the viability of replacing the traditional electricity generated by fossil fuel with an integrated PV-Battery Energy Storage System (PV-BESS). The key focus is whether it is technically feasible for this system to provide a similar capability to the traditional electricity generator in terms of power supply and system performance. Unlike previous research that primarily addresses energy production, this study emphasizes the technical aspect of the system performance.

6.2 Technical Performance Evaluation

The results from the simulation demonstrate the ability of the PV-BESS system to sustain its operation under changing climatic environments through different seasonal irradiances. The system efficiently provides for the required load demand and maintains appropriate voltages and energy balance in the process [1], [2].

In cases where the irradiances are high, the system mainly relies on the energy supplied by PV sources; conversely, when there is low irradiance, the role of the battery and the grid is greater [19]. In this way, the system sustains its operations, even with the intermittency of solar energy.

As regards the dynamic nature of the load variation applied to the system in the simulation, the system is shown to be responsive to sudden changes in the demands. Despite a significant load increase from 50 to 100 kW, causing the system to experience some level of disruption, the system manages to stabilize within a short time without any significant changes in voltage [24].

However, it must be understood that this particular simulation occurs within a short time frame and evaluates the transient response of the system.

6.3 Active Power Replacement Capability

One of the crucial aspects of using renewable generation as an alternative to fossil fuels is ensuring the continuous supply of active power in response to load requirements [19]. In the given structure, load balancing is accomplished via combined inputs from photovoltaic (PV) generation, battery energy storage systems (BESS), and the grid.

$$P_{load} = P_{PV} + P_{BESS} + P_{grid}$$

Based on the findings, PV generation offers a significant power supply under suitable circumstances, with the battery system assisting in addressing the disparity between power generation and consumption [17]. Nevertheless, the grid plays an essential role, especially during the low irradiance period and when the battery is limited by its state of charge.

As a result, the hybrid approach acts as a grid-interactive model, which reduces dependency on conventional sources of generation without compromising the stability of the system. It is crucial to highlight that the given design does not offer full grid independence [22].

6.4 Reactive Power and Grid Support

However, traditional fossil fuel-based power stations offer reactive power support through the natural attributes associated with synchronous generators. On the other hand, renewable energy sources use power electronic converters for the task [15].

In the suggested approach, the voltage source converter (VSC) allows independent control of the active/reactive powers through the control of the d-q currents:

- Active power control using the d-axis current
- Reactive power control using the q-axis current

The above control strategy allows providing reactive power support for voltage regulation purposes. The simulation has shown that the system can handle the need for reactive power and keep voltage levels within permissible limits [22].

However, it should be pointed out that there will be a limit to the available reactive power from the VSC, which would not match the inertial properties of the generator.

6.5 Economic Feasibility and Cost Justification

As shown in Chapter 6, the LCOE of the hybrid PV-BESS technology depends on cost assumptions and is variable. In ideal conditions, the LCOE estimates seem to be more expensive than fossil fuel-based power plants, which can be assumed without taking any other cost parameters into consideration.

However, this comparison cannot be considered accurate. Fossil-fuel–based plants have higher costs due to market dependency. On the contrary, there are fewer operating costs for PV-BESS plants but higher initial costs.

Furthermore, recent research shows that the cost of PVs and batteries is expected to fall continuously, making renewable energy sources economically advantageous over time [19], [22]. If environmental costs and energy security are considered, even more benefits will be provided by hybrid systems, especially in developing countries.

6.6 Integrated Technical-Economic Justification

The practicality of the replacement of the fossil fuel-based system is influenced by its technical efficiency and economic viability.

From a technical perspective, the hybrid PV-BESS system proves capable of:

- Balancing power during various operational modes
- Supplying reactive power
- Reacting to changes in dynamic loads

Economically, the system appears to have the potential to be competitive, especially concerning costs and environmental aspects.

However, it is important to emphasize that this system does not fully emulate traditional power plants in terms of inertia, massive dispatchability, and total autonomy from the grid. Instead, it represents a feasible alternative to or partial replacement of such systems.

6.7 Limitations and Critical Reflection

Despite the promising results, several weaknesses need to be mentioned:

- Dynamic simulation works on small time frames and cannot demonstrate operational behavior for longer periods.
- An economic model is too basic and does not include important financial factors, like discount factors or life cycle cost analysis.
- Degradation of batteries and their life cycle performance is not taken into account.
- System evaluation is performed using a small-scale setup, which may not reflect the situation with larger utility-scale power plants.

These facts prove that there is an urgent need for additional research on the subject.

6.8 Summary

In this chapter, an evaluation is carried out regarding the techno-economic feasibility of the hybrid solar PV/BESS system. The results show that while there is a great possibility of using this system to significantly lower the dependence on fuel-based electricity generation, it cannot match all functions of conventional power stations. The hybrid system can be seen as a realistic means of incorporating renewable energy into power systems.

Chapter 7

Conclusion And Future Work

7.1 Introduction

In this chapter, a conclusion will be drawn for the findings of this research regarding the feasibility of replacing traditional fossil fuel-based power plants with an energy plant that uses solar PV panels combined with BESS. In this research, an analysis was done using dynamic simulation through MATLAB/Simulink, along with techno-economic optimization through the REopt provided by the National Renewable Energy Laboratory. This is to determine whether the hybrid plant will be able to operate the same way as fossil-based power plants while remaining economically viable [18], [35].

7.2 Summary of Technical Findings

Based on the technical analysis, it has been confirmed that the suggested PV-BESS hybrid system is capable of operating reliably and steadily regardless of the changes in the environment and load parameters. In particular, the developed model by means of MATLAB/Simulink took into account all essential elements of the system, namely the PV panel, MPPT-based boost converter, BMS, VSC, and LC filter. Under all simulation situations - rain, summer, winter, and yearly average cases - the system had voltage stability and provided an uninterrupted power supply [6]. In particular, PV energy generation served as the main source of electricity, while the battery played a secondary role in cases of low solar radiation levels [19]. The connection with the grid became the backup in order to increase the system's reliability. An important conclusion of the analysis was related to the ability of the suggested system to function under varying loads. It has been found that the shift from 50 kW to 100 kW was achieved easily since the system had sufficient dynamic stability properties. The inclusion of the VSC and LC filter enabled the system to provide reactive power.

In general, these results prove the ability of a hybrid PV-BESS system not only to generate electricity but also to have grid-supporting functions similar to fossil fuel sources of energy [25].

7.3 Summary of Economic Findings

The techno-economic analysis performed with the help of REopt provides valuable information about the cost-effectiveness of the suggested arrangement. It allows discovering the combinations of the sizes of both photovoltaic (PV) arrays and battery packs, which would provide for the lowest Levelized Cost of Energy (LCOE) [35].

According to the findings, the cost-optimal configuration could produce energy with LCOE equal to no more than 0.0651 USD/kWh. It means that hybrid PV-BESS systems have great economic potential because there are almost no fuel costs, which would otherwise raise the LCOE significantly [19].

Although the initial expenses for the construction and installation of such a system may be rather high, its operating costs are relatively constant, so no increases in fuel prices would make a negative impact on LCOE [29]. Besides, the steady decline in prices of batteries and solar panels may make such systems even more cost-efficient in the future.

It proves the hypothesis that hybrid energy-producing systems could be viewed as an economically sound alternative to traditional fossil fuels [6].

7.4 Final Answer to Research Objective

The main objective of this thesis was to determine whether the hybrid PV-BESS (Photovoltaic Battery Energy Storage System) setup can be used to replace a fossil-fuel-based power station, both from a technical standpoint and an economical one. From the results that have been obtained, it is fair to state that the hybrid PV-BESS setup satisfies the set objective [24]. Firstly, from a technical perspective, the system has demonstrated its ability to supply active power, supply reactive power, and even remain stable during the process of operation, meaning that it functions like a regular fossil-fuel-based power station. Secondly, on the economic aspect, it is evident that through optimization, a good levelized cost of energy (LCOE) has been achieved. While the initial cost of setting up the system is higher, the non-dependency on fuel is an added advantage [33].

7.5 Limitations of the Study

However, there are some drawbacks associated with this thesis despite its extensive investigation. The economic model used in the paper is relatively simple and does not take into account any additional aspects such as operating and maintaining expenses, energy storage depreciation, inflation, and discounting. In this case, including all of the above-mentioned components would result in a more precise assessment of economic effectiveness. The simulation process was carried out in a very short period of time, namely five seconds, to assess dynamics; however, it may not reflect the whole system behavior. Furthermore, the irradiation and load data used in the investigation can be considered typical; nevertheless, they do not include all possible deviations that may exist in reality [7]. In addition, the limitation is associated with the assumption that the temperature and wind speed values in the REopt model remain steady [10], [13].

7.6 Recommendations for Future Work

Future research could improve on this study by using more accurate models. One approach is through the use of long-term simulations of the system to determine how well it performs under different conditions [7]. This will provide additional insight into the system's reliability and seasonality. The cost analysis can be improved further using lifecycle costing, which takes into account costs such as operation and maintenance costs, replacement costs, and monetary variables such as interest and inflation rates. This will help in determining the feasibility of the system. Further research could also include the use of different renewable energy sources, like wind power or hydrogen-based systems, which will enhance system reliability and flexibility. The use of advanced control systems, such as artificial intelligence and machine learning, can be used to improve system performance. In conclusion, further research can also involve scaling up the model for use in national grids and its effects on national energy systems, especially those in developing nations switching to renewable energy sources [24], [33].

7.7 Concluding Remarks

Through this study, one is able to conclude that hybrid PV and battery energy storage systems represent a feasible option for sustainable and resilient power production. The combination of technical feasibility and economic viability makes such systems a promising solution in addressing the problem of fossil fuel dependency and promoting the adoption of renewable energy around the world. These research conclusions add to the growing pool of knowledge in the field of hybrid renewable energy systems.

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