Synergy Optimization Algorithm of Heterogeneous Hybrid Energy Architecture to Enhance Resilience and Reliability in Intermittent Stochastic Power Network.

By

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A project report submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of Master of Engineering in Electrical and Electronic Engineering

Electrical and Electronic Engineering
Brac University
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DECLARATION

It is hereby declared that

1. The project submitted is my own original work while completing degree at Brac University.

2. The project does not contain material previously published, except where this is appropriately cited through full and accurate referencing.

3. The project does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.

4. I have acknowledged all main sources of help.

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APPROVAL

The project titled "Synergy optimization algorithm of heterogeneous hybrid energy architecture to enhance resilience and reliability in intermittent stochastic power network" submitted by

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of Fall, 2025 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Engineering in Electrical and Electronic Engineering on 18-05-2025

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ABSTRACT

Increasing of renewable energy sources in modern power networks has introduced challenges related to intermittency and stochastic variations that affects system reliability and resilience. This research proposes a Synergy Optimization Algorithm for a Heterogeneous Hybrid Energy Architecture to enhance power stability in an intermittent stochastic power network. The architecture integrates solar energy and generator based power when load shedding of grid occurs or ensuring grid independence while maintaining system reliability. A key challenge arises when low loads and high solar irradiance push generator operation below its minimum threshold (30%) that lead to potential tripping, cascading failures and financial losses.

The proposed optimization algorithm dynamically adjusts the synergy between solar and generator power ensuring load balance while minimizing blackout risks. Through mathematical modeling and simulation, the study evaluates the impact of varying solar irradiance and load conditions, incorporating constraints on generator operation. HOMER Pro software is utilized to simulate system performance and quantify financial losses due to power outages. The results demonstrate how the synergy optimization algorithm mitigates generator tripping, enhances system resilience and improves reliability offering a viable solution for industrial and off-grid hybrid energy systems. This research contributes to the field of hybrid energy systems by proposing a resilience-driven optimization approach, ensuring sustainable and uninterrupted power supply under stochastic conditions.

Keywords: Hybrid Energy Systems, Synergy Optimization, Stochastic Power Network, Resilience, Reliability, HOMER Pro Simulation, Solar, PV, Generator, Power.

DEDICATION

This work is dedicated to my parents for their endless love, support and encouragement.

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I would like to express my deepest gratitude to my supervisor, Prof. Dr. Md. Mosaddequr Rahman, for his invaluable guidance, support and encouragement throughout the course of this research. His insights and expertise were instrumental in shaping this Project & his advice and suggestions were of immense importance which helped in this work.

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CHAPTER1: INTRODUCTION

Bangladesh, a country with a rapidly growing population and increasing demand for energy is facing significant challenges in ensuring sustainable and reliable power generation. While nation made considerable strides in expanding its electricity grid, the gap between supply and demand remains substantial. Traditional sources of energy such as natural gas, coal and oil have been the cornerstone of Bangladesh's energy sector. However, these resources are finite, environmentally damaging and subject to global price fluctuations. As such the need for alternative renewable energy solutions have become a pressing concern.

1.1 BACKGROUND

Bangladesh's power sector has achieved universal electricity access with an installed capacity approximately 29,000 MW as of March,2025. However, challenges persist including frequent load shedding due to fuel shortages and rising demand. Electricity demand reached approximate 15,000 megawatts (MW), while the maximum generation capacity was approximate13,000 MW, indicating a shortfall of 2000 MW [1]**.** The industrial sector is significantly impacted with approximately 13.6% of its electricity demand unmet leading to an estimated 11.54% loss in industrial output [2]. To address these issues government plans to increase generation capacity aiming to meet a projected peak demand [3]. Additionally, there is a focus on expanding renewable energy predominantly from solar power [4].

Solar energy emerges as one of the most promising and viable options for Bangladesh. The country is located in a region with abundant solar radiation making it particularly suited for solar power generation. However, the challenge remains in harnessing solar energy efficiently particularly in terms of storage and reliability as solar photovoltaic (PV) systems are dependent on sunlight availability and can face issues related to intermittency. While renewable energy offers sustainability and cost advantages its variability poses risks to power system stability particularly in hybrid energy architectures that rely on multiple sources for continuous operation. In industries off-grid applications it ensures a reliable power supply requires a strategic balance between renewable sources and conventional generators.

1.2 PROBLEM STATEMENT

A Heterogeneous Hybrid Energy Architecture (HHEA) consisting of solar power and generator-based power, presents a promising solution to reduce dependence on grid electricity while promoting sustainability. However, in such a system maintaining operational stability is a critical challenge. Load demand continuously fluctuates throughout the day, while solar PV systems typically provide a relatively fixed output based on solar irradiance. Solar irradiance levels are high in Bangladesh energy demand often remains low during these peak solar hours. The national grid in Bangladesh is highly intermittent, with frequent load shedding occurring several times a day. This reduced system resilience, highlighting the need for smarter hybrid system design and control.

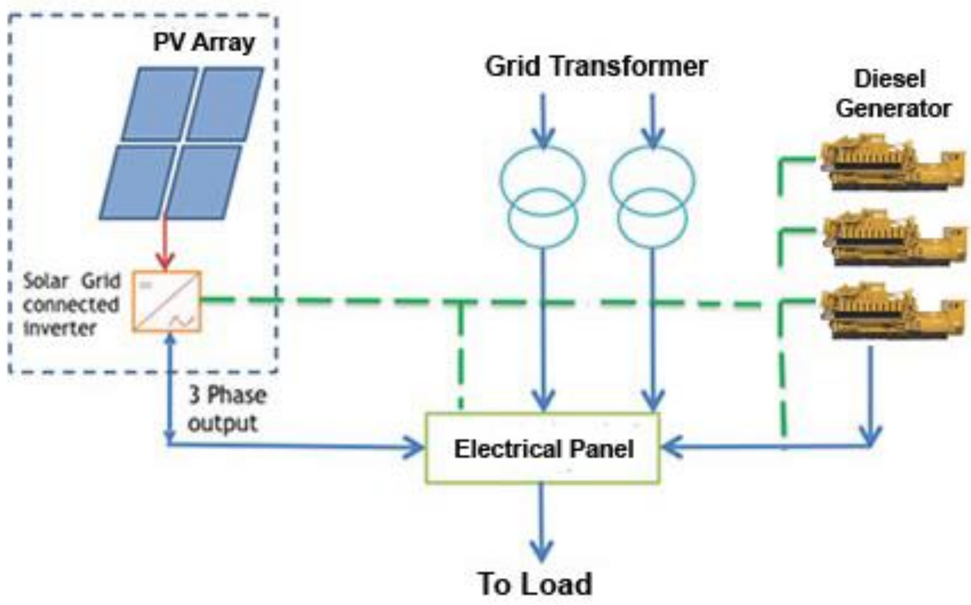

Figure-1.1: System Diagram of Heterogeneous Hybrid Energy Architecture

A key issue arises when high solar irradiance coincides with low load demand, reducing the generator's load below its minimum operational threshold. If the generator trips under these conditions, grid-tied solar power is also lost, leading to blackouts and financial losses for industrial operations. This issue underscores the need for an intelligent control mechanism to dynamically optimize power distribution between solar and generator sources.

1.3 RESEARCH OBJECTIVE

- The objective of this research is to develop a Synergy Optimization Algorithm that coordinates the operation of multiple heterogeneous energy sources like PV energy and conventional generators.
- To optimize energy management for better power output and control of HHEA by addressing practical operation constraints.
- To simulate and analyze system performance under various scenarios like blackout, load fluctuations using realistic load profiles and operational data.
- The ultimate goal is to improve the resilience and reliability of power networks under intermittent and stochastic conditions.

1.4 RESEARCH OUTCOME

The research outcome of this project will provide a comprehensive framework for optimizing the synergy between grid power, solar energy and generators in a hybrid energy system. By analyzing blackout risks, fuel consumption patterns and economic feasibility the study will propose an optimized operational strategy to enhance system reliability and resilience. Results will demonstrate how it can prevent blackouts, minimize fuel costs and improve overall efficiency. Additionally, the study will highlight the environmental effect to ensure sustainable operation. Ultimately this research will contribute to the development of a cost-effective, resilient and sustainable hybrid power network suitable for industrial applications.

1.5 RESEARCH OUTLINE

A research outline is a structured summary that presents the key components of a study in a concise format. In the research work first there is Introduction, where the background of the topic is explained. Then, Problem Statement and the Objectives of the research was described.

Next, there is a Literature Review, discussing previous relevant works and will find out the research gap. In the Methodology section System modeling is explained and go through with the work flow diagram to develop the algorithm based on the system modelling. After that Mathematical Model of Algorithm of the research was developed and the Simulation is done using re-known software HOMER Pro.

In the Result & Analysis section, multiple analysis is being carried out that includes technological, financial & environmental analysis. Finally, it is concluded with the Conclusion, summarizing the outcomes and getting the recommendations. Here to find out the limitations and possible directions of future scope of my research at the last.

This outline serves as a roadmap, guiding the research process by clarifying the focus, scope, and approach. It helps to organize thoughts, identify gaps and ensure coherence throughout the research.

CHAPTER 2: LITERATURE REVIEW

The Literature Review is a crucial for thesis as it lays the foundation for the current state of knowledge in a particular research area. It builds a strong foundation by analyzing Research, theories & technologies. It helps to identify research gaps & unresolved problems that explore the need for the current work out. In the context of my thesis the literature review serves multiple purposes. It examines prior works on hybrid energy systems, resilience in power networks, stochastic modeling and optimization algorithms. Specifically it evaluates existing energy management strategies, identifies limitations in handling intermittency and uncertainty and investigates various architectures for integrating renewable and non-renewable sources. This review highlights the complexity of managing heterogeneous hybrid systems and justifies the development of a new synergy optimization algorithm tailored to enhance both reliability and resilience in dynamic grid environments. Thus the literature review directly supports the objectives of proposed research by demonstrating what has already been done and what remains to be achieved.

2.1 REVIEW OF EXISTING RESEARCH

Hybrid Energy System (HES) has gained prominence due to their potential to enhance energy resilience and reliability in intermittent stochastic power networks. The integration of solar power and generator-based energy solutions provides an effective strategy to mitigate grid dependency. However ensuring optimal synergy in such systems remains a challenge especially in the absence of energy storage solutions. This literature review explores several studies on Heterogeneous Hybrid Energy Architecture due to power disruptions with a focus on various research contributions.

2.1.1 Hybrid Energy Systems: Overview, Importances and Challenges

Hybrid Energy System (HES) typically combine multiple power sources, including renewable energy and conventional generators to enhance system reliability [5]. Several studies have highlighted the advantages of such configurations in reducing fuel consumption and emissions while improving sustainability [6]. However intermittency of renewable sources like solar power poses a critical challenge. The absence of a battery storage system increases dependence on precise control mechanisms to prevent generator underloading and potential system failures [7].

In [8] a hybrid energy system combining solar and diesel generators was analyzed for industrial applications. The study emphasized the importance of load forecasting to prevent blackout scenarios caused by inadequate generator loading. Another research [9] investigated power quality issues in hybrid energy microgrids noting that voltage fluctuations and harmonics can lead to generator instability further exacerbating blackout risks. Recent studies have focused on optimizing these systems to reduce active losses and enhance efficiency.

2.1.2 Renewable Energy Integration in Hybrid System

The integration of Renewable Energy System (RES) into hybrid systems introduces variability and uncertainty due to their intermittent nature. To address these challenges advanced optimization algorithm has been developed. A notable example is the application of the Zebra Optimization Algorithm (ZOA) for the optimal design of off-grid hybrid systems which has shown promising results in enhancing system performance and reliability [10].

2.1.3 Resilience and Reliability

The resilience of hybrid systems is crucial for industrial applications where even brief power outages can lead to significant financial losses. Reliability improvement strategies such as robust control algorithms and predictive maintenance have been widely studied [11].

A study in [12] proposed a stochastic optimization model to enhance reliability in off-grid hybrid microgrids considering weather uncertainties. The model demonstrated that incorporating adaptive control strategies significantly reduced blackout probabilities. Similarly [13] explored a resilience-driven approach where machine learning-based fault detection was employed to preemptively identify failure points in hybrid networks.

HOMER Pro has been widely used for reliability assessments in hybrid systems. In [14] simulations using HOMER Pro illustrated how different dispatch strategies influence system resilience highlighting the importance of optimal generator scheduling.

2.1.4 Intermittency and Stochastic Variability in Renewable Energy

The stochastic nature of RES poses significant challenges to the stability and reliability of power networks. Methods such as Monte Carlo simulations combined with Newton-Raphson power flow analysis have been employed to assess and enhance the reliability of grid-connected hybrid renewable energy systems that effectively addressing the uncertainties associated with RES [15].

2.1.5 Minimum Generator Loading Constraint

In hybrid system maintaining generators above a minimum loading threshold is crucial to prevent inefficiencies and potential tripping. Energy Storage Systems (ESS) play a vital role in mitigating the variability of RES supporting grid stability and enabling energy consumption time-shifting. The strategic integration of ESS can help maintain optimal generator loading and enhance overall system resilience [16].

2.1.6 Synergy Optimization Strategies in Heterogeneous Hybrid System

Synergy optimization focuses on the coordinated operation of diverse energy resources to enhance system resilience and reliability. Advanced decision support frameworks employing Multi Criteria Decision Making (MCDM) have been introduced for optimizing multi-energy network scheduling effectively integrating conventional and alternative energy sources while addressing uncertainties [17].

Optimization techniques have been applied to hybrid energy system to enhance reliability and minimize operational costs. These include balancing multiple objectives such as cost, reliability and environmental impact. Multi Objective Optimization (MOO) strategies have been employed in energy management systems of hybrid renewable energy systems to minimize costs and reduce the likelihood of power supply loss [18].

In [19], the study indicates that the fluctuations in the output power of PV systems make it difficult to predict their output. This study focuses on using a suitable storage battery along with the PV system and a diesel generator. It analyzed the impacts of implementing the economic benefits that the PV system owner could gain.

By managing uncertainties in power generation and demand, a Multi Stage Stochastic Robust Optimization model has been proposed for resilience management in smart power distribution system effectively coordinating operational measures [20].

Combining different heuristic methods to improve optimization outcomes, an efficient scenario-based stochastic energy management approach utilizing a hybrid evolutionary algorithm has been developed for distribution networks with distributed generation by achieving a balance between operational cost and energy not supplied [21].

2.1.7 Blackout Impact and Financial Loss Estimation

The financial implication of blackout in industrial sectors has been extensively analyzed. In [22] the economic losses due to unplanned power outages were quantified using real-time production data, showing a direct correlation between blackout duration and revenue loss. The study emphasized the role of hybrid energy optimization in mitigating these financial risks.

Research in [23] used Monte Carlo simulations to assess financial impacts on manufacturing industries concluding that backup power systems alone are not sufficient. an optimized energy mix is necessary to ensure continuous operations. Another study [24] introduced a novel approach to quantify blackout-related losses using time-series load data to prove predictive control mechanisms could significantly reduce economic losses.

2.1.8 Simulation and Analysis

In some studies simulation tools are used for the technical and economic analysis of hybrid energy system. Open-source energy system models like PyPSA (Python for Power System Analysis) have been utilized for simulating and optimizing electric power systems supporting the integration of renewable energy sources [25]. It facilitates comprehensive financial impact analysis including cost-benefit assessments and evaluations of financial losses due to potential blackout. The literature indicates that optimizing hybrid energy systems requires a multi faced approach that incorporates predictive analytics, robust control strategies and monitoring. Addressing blackout induced financial losses through improved system reliability remains a crucial area of research.

2.2 SUMMARY OF DISCUSSED LITERATURE

The literature review highlights the critical aspects of Hybrid Energy Systems (HES) including their importance, challenges and optimization strategies. Hybrid system integrate Renewable Energy Sources (RES) with conventional generators enhance reliability but they introduce issues such as intermittency, synchronization and generator underloading. Studies emphasize the necessity of precise load forecasting, robust control mechanisms and predictive analytics to prevent blackouts and ensure efficient energy management.

Renewable energy integration presents challenges in terms of power quality and variability necessitating advanced dispatch strategies and real-time monitoring. Simulation tools like HOMER Pro and PyPSA have been widely used for techno-economic analysis demonstrating that strategic energy dispatch can reduce costs and enhance system reliability. This literature provides a strong foundation for the project as it aligns with the need for a synergy optimized hybrid energy system that enhances resilience in intermittent stochastic power networks. The research outcomes reinforce the necessity of predictive energy management and optimization models which directly relate to the project objective of improving reliability and minimizing financial losses in power system.

2.3 SIGNIFICANCE OF RESEARCH

The literature review provides a comprehensive understanding of the challenges, opportunities and optimization strategies making it a crucial foundation for this research. It establishes the importance of integrating Renewable Energy System (RES) with conventional power generation to improve sustainability while addressing intermittency and reliability concerns.

By reviewing these literatures, the research significance can be concluded. From literature studies it becomes evident that without proper synchronization, load forecasting and control mechanisms, hybrid system is prone to inefficiencies, generator tripping and blackout, leading to significant financial losses.

Thus it needs to find out the optimization technique to minimize generator tripping and blackout.

The primary contribution of proposed research lies in the development of a Synergy Optimization Algorithm tailored for a Heterogeneous Hybrid Energy Architecture that enhances the resilience and reliability of power networks operating under intermittent and stochastic conditions. Unlike traditional approaches proposed work introduces a multi-criteria optimization model that synergistically coordinates diverse energy sources including renewables and conventional generators. Additionally, this model incorporates priority-based load management, grid blackout behavior and operational fluctuations making it more applicable to practical industrial settings.

This research also contributes a detailed simulation-based evaluation using realistic load profiles and grid scenarios highlighting how hybrid coordination can maintain power system stability and improved response to disruptions. This integrated framework offers actionable insights dealing with complex, uncertain grid environments.

CHAPTER 3: METHODOLOGY

This research follows a structured methodology to develop and evaluate the Synergy Optimization Algorithm for a Heterogeneous Hybrid Energy System, ensuring improved resilience and reliability under intermittent stochastic power conditions. The methodology consists of four key phases.

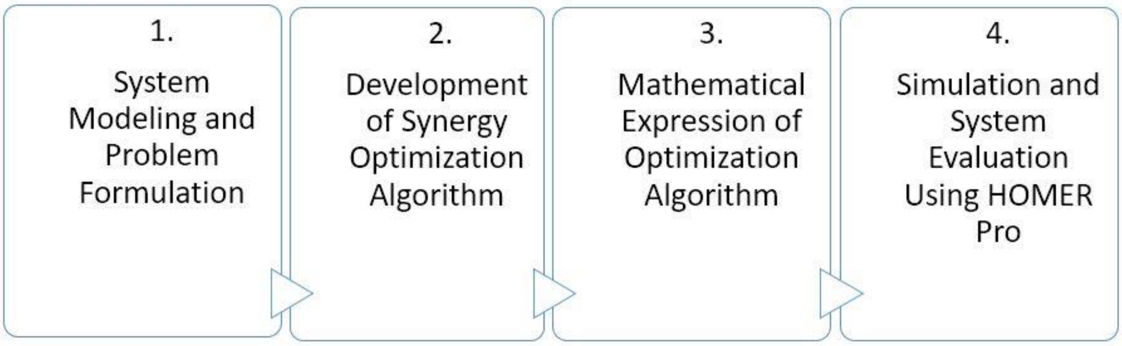

Figure-3.1: Key Phases of Four Steps Methodology

3.1 SYSTEM MODELING AND PROBLEM FORMULATION

System modeling and problem formulation are foundational steps in understanding, analyzing and solving complex problems. System modeling involves creating representations of a system's components, processes and operations of the system.

The Heterogeneous Hybrid Energy System is designed for resilience and reliability integrating two grid connections, two generators, one solar power source and one standby generator. Under normal conditions the system operates with both grids, two generators and solar energy while the standby generator remains idle. In the event of grid failure due to load shedding the system automatically transitions to backup power, running on two generators and solar energy. To optimize power usage, non-priority loads are automatically disconnected when the grid becomes unavailable ensuring that critical loads receive uninterrupted power. Bus couplers and tie breakers are strategically placed to manage power flow and switching between sources.

The hybrid power system is a 400V, 3-phase, 50Hz network designed for reliability and resilience in an industrial setup. The system consists of two grid utility connections, three generators, a 1000kWp solar PV system and a well-defined load distribution network. The total load is 2.5MW, categorized into priority and non-priority loads, ensuring an optimized energy distribution strategy. Bus couplers, tie breakers, energy meters and HMI-based monitoring are integrated for safe and efficient operation.

3.1.1 POWER SOURCES

Power sources in this project include a combination of grid power, diesel generators and solar photovoltaic (PV) energy, forming a heterogeneous hybrid energy system. Since the system does not include battery storage real-time synchronization and generator loading management are essential to prevent instability and blackout. The synergy between these power sources is optimized using control strategies in an intermittent stochastic power network.

3.1.1.1 Grid Supply

The system receives power from two independent 11kV grid utility connections of Utility-1 & Utility-2. Grid power is supplied via a 33kV common feeder stepped down to 11kV through a 33/11kV transformer with OLTC(ON LOAD TAP CHANGER) to maintain the voltage in desired level. Further, the 11kV is stepped down to 400V using two 11kV/400V, 2000kVA transformers to match the load demand. Grid power is subject to load shedding, requiring backup power sources.

3.1.1.2 Diesel Generator

The system has two 1000kVA generators (GEN-1, GEN-2) and one 500kVA (GEN-3) generator. These generators operate in an N+1 redundancy scheme, meaning two run under normal backup conditions while one remains on standby. Generators are equipped with AVR (Automatic Voltage Regulation) and Gov too. Synchronization panels and governor controls are incorporated for stable operation.

3.1.1.3 Solar Power System

The system includes a 1000kWp solar PV array with suitable grid-tied inverters. It designed to supply power during daytime operation, reducing dependency on fossil fuels and configured for maximum penetration without destabilizing generator load balancing.

In the year 2024, the total solar irradiance varied significantly across the months, summing up to 1,478.47 kWh/m². The highest irradiance was recorded in April at 165.24 kWh/m², closely followed by March with 163.24 kWh/m², indicating peak solar energy availability during these months. The month May also contributed significantly with 150.92 kWh/m². In contrast, the lowest irradiance was observed in January (84 kWh/m²) and August (88.13 kWh/m²), suggesting reduced solar energy potential during these periods.

Table-3.1: Total Monthly Global Irradiance in the Year 2024 in Dhaka [21]

Month (In the year of 2024)	**Total Irradiance (kWh/m2)**
January	84
February	142.36
March	163.24
April	165.24
May	150.92
June	104.54
July	134.76
August	88.13
September	109.95
October	111.55
November	119.15
December	104.59
Total	**1478.47**

The mid-year months, particularly June and July, showed fluctuating irradiance levels, with June at 104.54 kWh/m² and July slightly higher at 134.76 kWh/m².

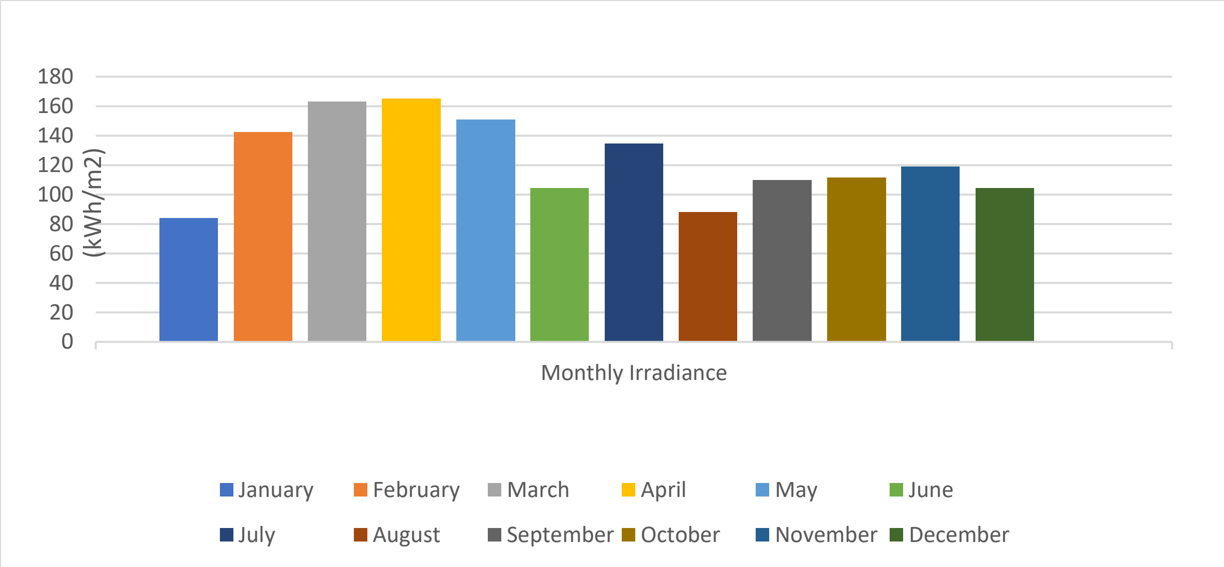

Figure-3.2: Total Monthly GI in the Year of 2024 in Dhaka

The graph illustrates the monthly total Global Horizontal Irradiance (GHI) measured in Dhaka by a sun tracker. The irradiance values fluctuate, with the highest levels recorded on March & April. The consistent variations throughout the year highlight the intermittent nature of solar energy, emphasizing the need for optimized hybrid energy system to ensure reliable power generation.

3.1.2 LOAD DISTRIBUTION & PRIORITY MANAGEMENT

The total Industrial load is 2.5MW divided into priority and non-priority loads to optimize power availability during grid failures. Where Priority Load is 1.0MW that Must be powered at all times. Non-Priority Load is 1.5MW that automatically disconnected during grid failure.

Table-3.2: Industrial (Chemical Industry) Load Distribution

Load Section	Priority	Description
Office Building (OB-1)	❌ (Non-Priority)	Administrative functions.
Process Plant-1	✅ (Priority)	Critical industrial process operations.
Process Plant-2	❌(Non-Priority)	Can be disconnected during grid failure.
Warehouse	❌(Non-Priority)	Storage facility with intermittent power needs.

Treatment Plant	✅ (Priority)	Water treatment and essential processing.
Auxiliary Loads	❌(Non-Priority)	Includes non-essential operations.

3.1.3 OPERATIONAL SCENARIOS

In Normal Operation when Grid Available both Utility-1 and Utility-2 supply power through transformers to the industrial load. Generators remain on standby and solar PV supplies power to reduce grid dependency. The HMI and energy meters monitor power distribution. When Grid Fails due to load Shedding & both grid unavailable, non-priority loads (1.5MW) are disconnected automatically. Generators GEN-1 & GEN-2 start and synchronize to supply the 1.0MW critical load. Solar continues to operate reducing fuel consumption. Bus couplers and tie breakers enabled closing for balanced power distribution. During Generator Maintenance if one generator (GEN-1 or GEN-2) unable to supply power the standby generator (GEN-3) automatically starts. Load balancing ensures no overloading occurs. Priority loads remain operational. When grid power is back it will synchronize with generator power and the system gradually reconnects non-priority loads to avoid power surges. Generators are in synchronize mode with the grid and once stable, they are either Shut down to save fuel or kept in a standby mode for redundancy. The solar system continues to operate in a grid-tied mode reducing grid power consumption.

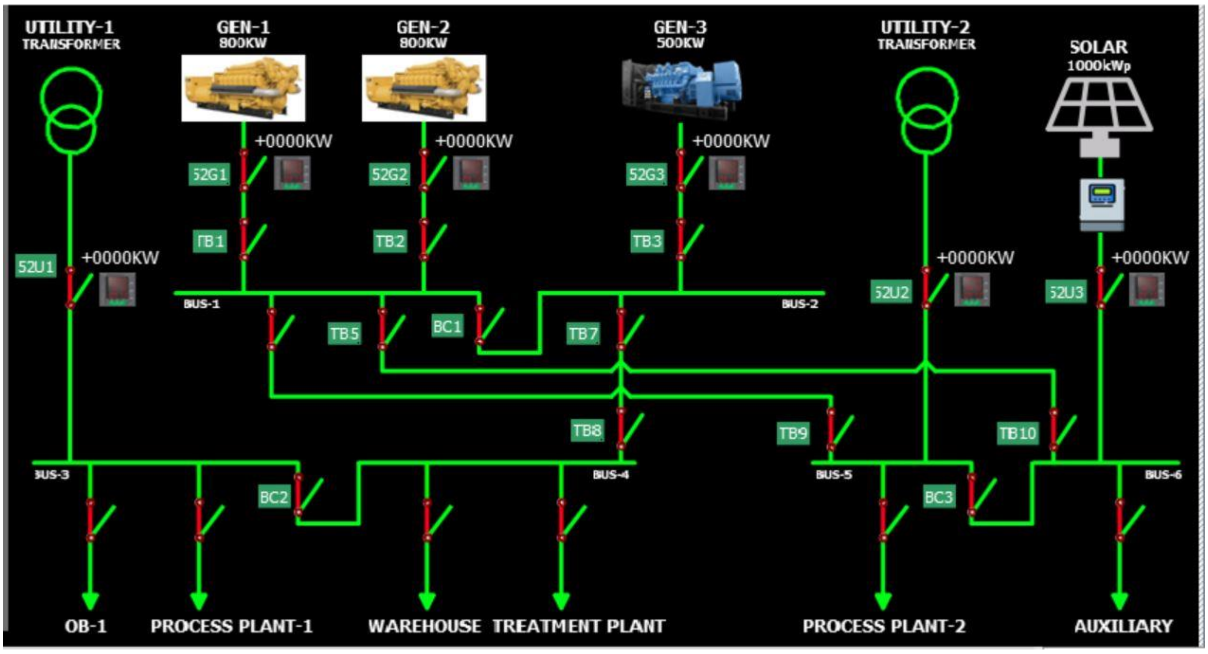

Figure-3.3: System Architecture of Heterogeneous Hybrid System

In the hybrid energy architecture power distribution and switching are managed efficiently through a well-structured bus system, which ensures seamless power flow, redundancy and load balancing. The system consists of multiple buses, bus couplers (BC) and tie breakers (TB) that facilitate flexible power routing and system stability.

The bus is a critical component of the power distribution network acting as a centralized connection point for power sources and loads. It enables the seamless transfer of electricity between the grid, generators and solar inverters, ensuring stable and coordinated power distribution. In this system, multiple buses are strategically arranged. Bus-1 & Bus-2 are connected to Utility-1 and Utility-2 via transformers, forming the primary power intake points. Bus-3 to Bus-6 used to distribute power to different industrial loads such as Process Plant-1, Process Plant-2, Warehouse, Treatment Plant Auxiliary, and the Office Building. Each bus is designed to handle specific power loads, ensuring smooth load distribution without overloading any single segment of the system.

3.1.4 SYSTEM COMPONENT

A Bus Coupler (BC) is a switching mechanism that allows different buses to be connected or isolated as needed. It enhances system flexibility and reliability by enabling power transfer between buses under different conditions. It allows buses to be linked during normal operation to maintain balanced power distribution. BC can Isolates faulty sections of the network in case of power faults or maintenance activities. It also Reconfigures the power network dynamically to ensure continuous operation, even if a primary source (grid or generator) fails. Under normal conditions the bus coupler remains closed connecting different bus sections to form a continuous power network. In case of a failure or maintenance, the bus coupler is opened, ensuring that faults do not propagate across the system.

A Tie Breaker (TB) is a specialized circuit breaker that serves to connect or disconnect power sources, buses or loads under different operational scenarios. It plays a key role in source switching, redundancy management and load isolation. It ensures controlled switching between grid, generator and solar power. TB Prevents back feeding of power into a failed section of the network & supports automatic load shedding by isolating non-priority loads during grid failures. TB also allows synchronization of generators before they are connected to the bus system. In Normal Grid Operation tie breakers between buses remain closed. It ensuring full power availability to all loads. At the time of Grid Failure condition tie breakers disconnect non-priority loads and ensure only essential operations continue. Before a generator connects to the bus the tie breaker ensures proper voltage and frequency matching. Tie breakers help control the safe connection and disconnection of solar power based on grid conditions.

The integration of buses, bus couplers and tie breakers ensure flexible, reliable and intelligent power distribution. Bus couplers allow interconnection or isolation of different sections while tie breakers enable safe switching and load prioritization. Together, they enhance system resilience, prevent power outages and optimize energy usage ensuring seamless operation under normal, failure and maintenance conditions.

To ensure safe operation and prevent power disturbances, all circuit breakers are interlocked with proper synchronization logic. No breaker can be closed unless voltage, frequency and phase angle match within acceptable limits. Generators are synchronized before connection, ensuring smooth transitions without voltage spikes. Similarly grid-tie inverters are designed for seamless integration, preventing back feed issues and voltage imbalances.

In case of a short circuit or overload, the system employs protective relays fast-acting circuit breakers and overcurrent protection devices. If a generator or grid transformer trips the system automatically isolates the faulty section via bus couplers and tie breakers, ensuring the rest of the network remains operational. If both the grid fail the system enters blackout mode, which is avoided by ensuring at least one generator is always running.

This hybrid energy architecture ensures continuous and reliable power supply, integrating grid, diesel generators and solar PV with a well-structured priority-based load management system. The automated power transition mechanism, real-time HMI monitoring and intelligent switching using bus couplers and tie breakers minimize financial losses due to blackouts while improving overall energy efficiency.

The primary problem in the system lies in the mismatch between fluctuating load demands and the fixed energy output from solar PV systems, despite high solar irradiance levels. This challenge is further compounded by the unreliable national grid, characterized by frequent load shedding and low resilience. The current infrastructure fails to effectively balance energy generation and consumption throughout the day.

Therefore, the problem formulation centers around designing an optimized Heterogeneous Hybrid Energy System (HHES) that intelligently integrates energy sources to ensure stable, resilient and efficient energy supply.

3.2 DEVELOPMENT OF SYNERGY OPTIMIZATION ALGORITHM

The core of the methodology involves designing an optimization algorithm that ensures stable and efficient power flow within the hybrid system. The algorithm focuses on Real-time Power Management. Adjusts solar PV output to prevent generator tripping and ensures minimum generator loading (≥30%) at all times.

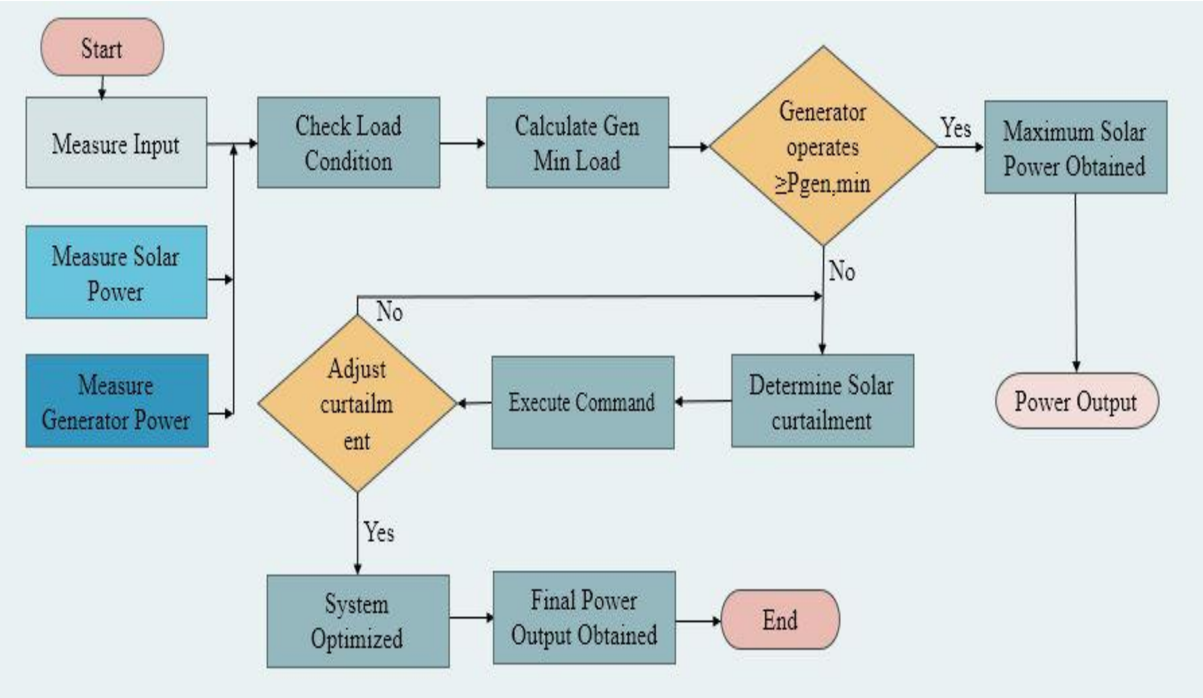

Figure-3.4: Work Flow Diagram of Synergy Optimization Algorithm

The algorithm involves solar PV, diesel generators and the grid. Instead of optimizing each energy source in isolation, synergy optimization looks at how these sources can work together efficiently, supporting one another in real-time based on load demand, solar availability and generator constraints.

This algorithm enhance reliability optimization reduces the frequency and duration of blackouts, maintains system resilience against fluctuations in solar irradiance. This algorithm also indicating financial loss minimization, estimates blackout costs and optimizes operations to reduce economic losses. The algorithm is designed using mathematical optimization techniques and will be implemented in HOMER Pro for validation.

3.3 MATHEMATICAL EXPRESSION

3.3.1 System Consideration and Definitions

- Solar Power (P_{solar}): Power generated by solar panels.
- Generator Power (P_{gen}): Power output from generator.
- Total Load ($L(t)$): The load connected to system at time t.
- Grid Power (P_{grid}): Assumed to be 0 since the grid is off.
- Generator rated Capacity ($P_{gen,\ max}$): Rated capacity of generator.
- Generator Minimum Loading ($P_{gen,min}$): Generator must operate at a minimum of 30% of its rated capacity ($P_{gen,max}$).

3.3.2 Power Balance Equation

Total load is supplied by the combined output of all power sources.

$$L(t) = P_{solar}(t) + P_{gen}(t) + P_{grid}(t) \tag{3.1}$$

With grid power off,

$$P_{grid}(t) = 0$$

Thus,

$$P_{solar}(t) + P_{gen}(t) = L(t) \tag{3.2}$$

3.3.3 Generator Loading Constrain

To maintain generator at a minimum of 30% loading, generator's output must satisfy,

$$P_{gen}(t) \geq 0.3 \times (P_{gen,max})$$

If total load *L(t)* is too low to maintain generator's minimum loading, solar power must be curtailed.

3.3.4 Solar Power Curtailment

When P_{solar} exceeds the load required to ensure the generator's minimum loading, Solar Inverter will limit its output to balance the system. Define the curtailed solar power ($P_{solar,\ curt}$) as,

$$P_{solar,\ curt}(t) = \min\left(P_{solar,\ avail}(t),\ L(t) - P_{gen,\ min}\right) \tag{3.3}$$

Where,

$P_{solar,\ avail}(t)$ is Available solar power based on irradiance.

$L(t) - P_{gen,\ min}$ is Maximum solar power that can be used while maintaining generator's minimum loading.

Thus, curtailed solar power is,

$$P_{solar}(t) = P_{solar,\ curt}(t), \qquad \text{if } P_{solar,\ avail}(t) > \mathrm{L}(t) - P_{gen,\ min} \tag{3.4}$$

$$P\ solar = \begin{cases} P\ solar, curt\ (t),\ \text{if } Psolar, avail\ (t)\ >\ \mathrm{L}(t) - Pgen, min \\ P\ solar, avail\ (t), otherwise \end{cases} \tag{3.5}$$

3.3.5 Generator Power Output

Generator will supply the remaining load after accounting for solar power,

$$P_{gen}(t) = L(t) - P_{solar}(t) \tag{3.6}$$

Subject to constraint,

$$P_{gen}(t) \geq P_{gen,\ min}$$

If $L(t) < P_{gen,\ min}$, generator must operate at $P_{gen,\ min}$, and any excess solar power will be curtailed.

3.3.6 Control Algorithm for Solar Inverter

To implement the above logic a control algorithm for solar inverter is designed as follows,

a. Measure Inputs:

   i. Real time total load $L(t)$.

   ii. Generator output $P_{gen}(t)$.

   iii. Available solar power $P_{solar,\ avail}(t)$.

b. Calculation of Minimum generator Loading:

$$P_{gen,\ min} = 0.3 \times (P_{gen,max}) \tag{3.7}$$

c. Determine Solar Curtailment:

$$P_{solar}(t) = L(t) - P_{gen,\ min} \tag{3.8}$$

Otherwise,

$$P_{gen}(t) = L(t) - P_{solar}(t) \tag{3.9}$$

3.3.7 System Optimization

To maximize solar power utilization while ensuring the generator operates at or above 30% loading, define the objective function,

$$\text{Max} \int_t P_{solar}(t)\, dt$$

Subject to,

Power balance,

$$P_{solar}(t) + P_{gen}(t) = L(t) \tag{3.10}$$

Generator loading,

$$P_{gen}(t) \geq P_{gen,\, min}$$

Solar power constrains,

$$0 \leq P_{solar}(t) \leq P_{solar,\, avail}(t)$$

This model ensures stability and efficiency in a hybrid energy system, maximizing solar utilization while protecting the generator from operating below its minimum load threshold. Mathematical expressions play a crucial role in this project by formulating the operational constraints, optimization objectives and system dynamics of the hybrid energy architecture. The energy balance equation ensures that the total generation from solar, grid and generators meet the instantaneous load demand while maintaining system stability. The minimum generator loading constraint is mathematically modeled to prevent underloading, which could lead to generator tripping and subsequent blackout. Additionally, stochastic variability in solar power generation is addressed using probabilistic models, ensuring that fluctuations do not disrupt system reliability. The reliability index and blackout probability are derived using statistical formulations to evaluate system resilience under different operational scenarios.

3.4 SIMULATION USING HOMER PRO

These mathematical models are simulated into HOMER Pro, validating the control strategy and ensuring optimal synergy between heterogeneous energy sources while maintaining a stable power supply. The simulation involves to define its parameters.

3.4.1 Defining System Components

The system integrates grid power, diesel generators (G1, G2, G3) and a solar Photo Voltaic (PV) system to optimize energy utilization. There are generators (GEN-1, GEN-2) of 1000kVA each and one 500kVA (GEN-3) generator. Solar capacity is 1000kWp. The architecture is structured around a centralized bus configuration, enabling efficient power distribution and seamless switching between energy sources based on availability, load demand and system constraints.

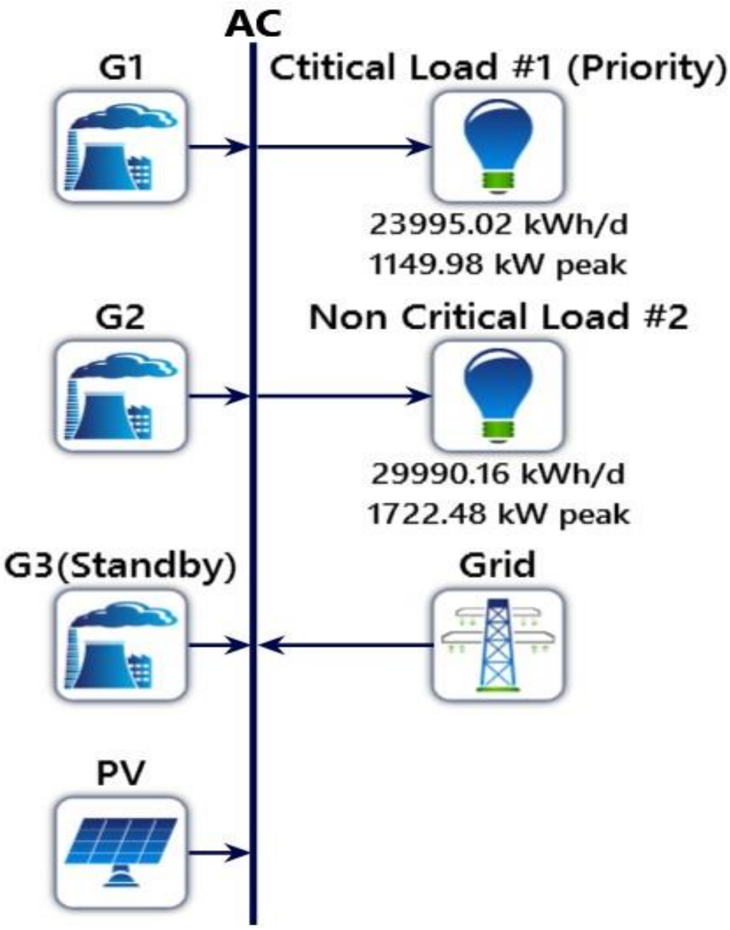

Figure-3.5: System Schematic Diagram for Simulation

3.4.2 Variability in Solar GI and Load Dynamics

The solar Photo Voltaic (PV) system in this project plays a critical role in reducing dependency on conventional power sources while enhancing energy resilience. The system includes a 1000 kWp solar installation, which effectively contributes around 800 kW under optimal irradiance conditions. The grid-tied inverters facilitate seamless integration by converting DC solar output into AC, ensuring synchronization with the grid and generators. However, due to the absence of battery storage, at least one generator must always be running alongside solar power to maintain system stability. If all generators shut down while the grid is unavailable, the solar system will trip, leading to a blackout. The system architecture is designed to maximize solar utilization during daytime hours, reducing fuel consumption and lowering operational costs while maintaining grid and generator stability.

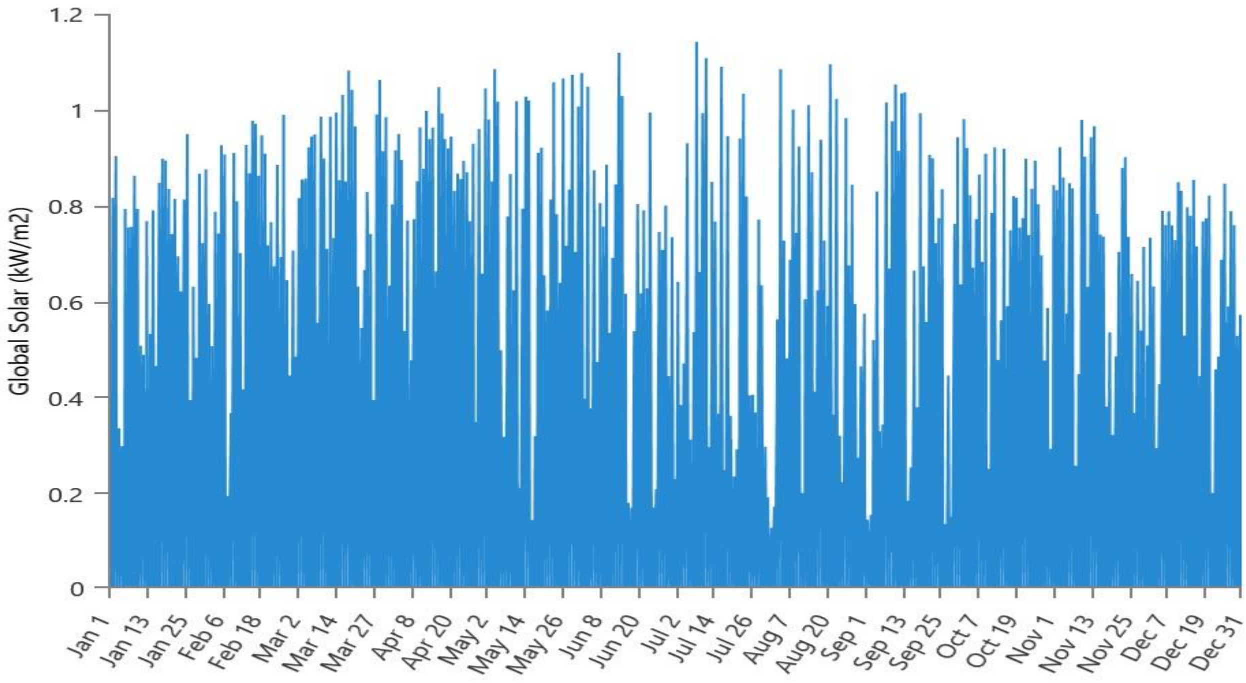

Figure-3.6: Variability in Solar Irradiance Dynamics

The total Solar Global Irradiance (GI) in Dhaka for the year 2024 was estimated using HOMER Pro. It shows Global Solar Irradiance in kW/m² on the y-axis over a year. Dates from January 1 to December 31 on the x-axis. Solar irradiance values vary daily, generally ranging between 0.2 to 1.1 kW/m², with the highest peaks occurring between March and July. It representing daily load variations throughout the year. Daily average GI is approximately 5.01 kWh/m²/day. This high level of solar irradiation highlights strong potential for harnessing solar energy throughout the year. It indicates, high irradiation can lead the system unstable while grid tie inverter running with generator in certain condition

The load profile for the HOMER Pro simulation is structured to represent the realistic industrial demand variations throughout the day and across the year. Daily variations exist due to machine operations, process plant activities and worker shift changes, creating a fluctuating power demand pattern. The total connecting load ranges from 1.8 MW to 2.5 MW, with a priority load of 1 MW that must be maintained even during grid failures.

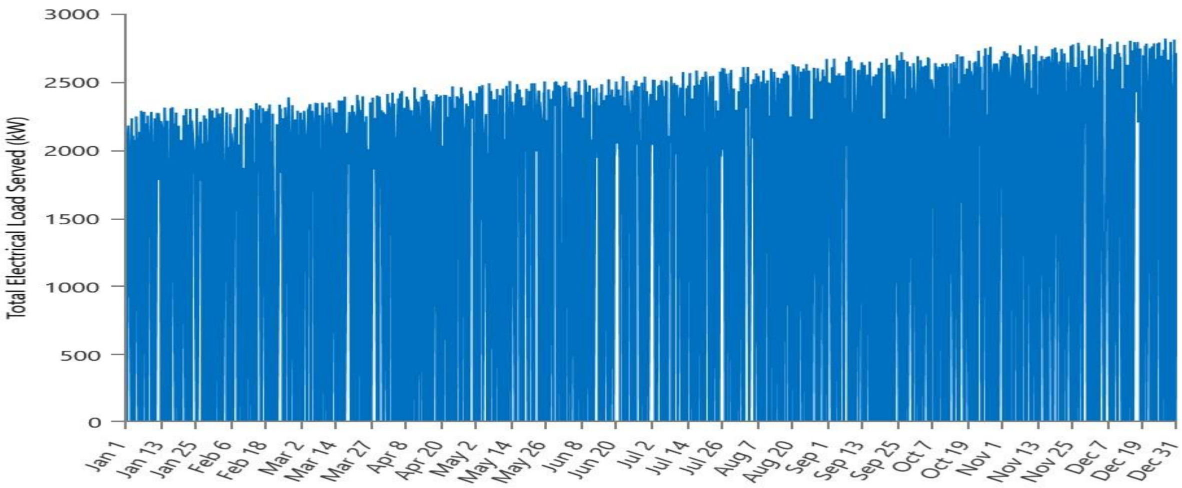

Figure-3.7: Industrial Load Profile of a Chemical Industry

Industrial energy consumption is highly dynamic, influenced by production cycles, shift changes and seasonal variations. Typically peak demand occurs during operational hours when heavy machinery and production lines are active. In this study, the load profile exhibits three primary demand shifts per day, corresponding to worker schedules and machine startup/shutdown cycles.

In the Load Profile, the graph (figure-3.7) displays the Total Electrical Load Served (in kW) on the y-axis against time (from January 1 to December 31) on the x-axis, representing daily load variations throughout the year. The load values fluctuate within approximately 2500 kW. It indicates, Industrial loading is highly dynamic, influenced by machine operations, process plant activities and worker shift changes.

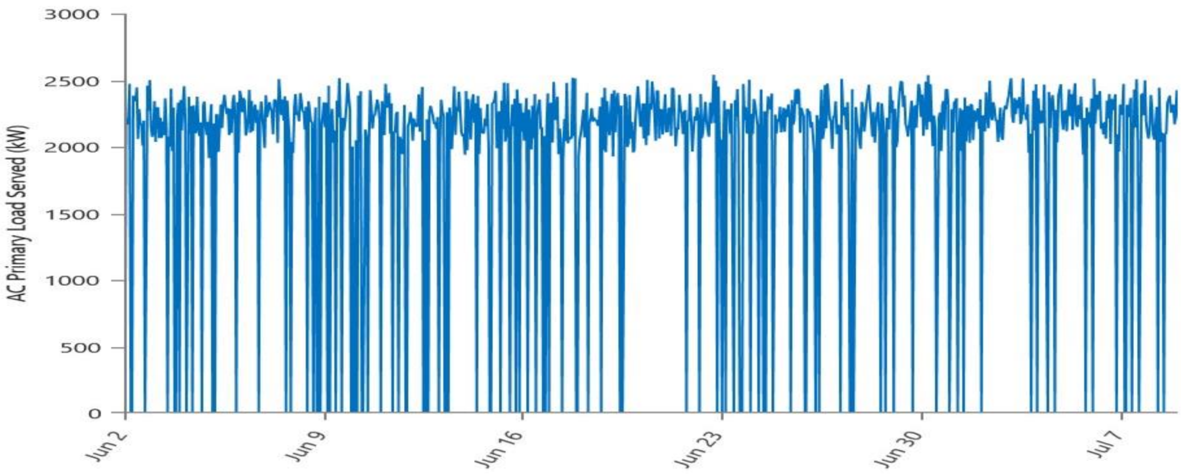

Figure-3.8: Variability in Load Dynamics

The graph (figure-3.8) illustrates the AC Primary Load Served (kW) over a period from June 2 to July 7 approximately for one month. The X-axis representing time (dates) and the Y-axis showing power delivered in kilowatts (0–3000 kW). Most values range between 2000 and 2500 kW, indicating that the system generally meets the expected load demand. However, the graph also reveals numerous sharp drops to 0 kW, indicating frequent service interruptions such as blackouts, generator delays, or load shedding events.

These interruptions are irregular but recurrent, suggesting a stochastic operational environment. Despite the overall stability, the presence of such drops emphasizes the need for an optimized energy management system that can ensure uninterrupted power delivery, especially to priority loads.

The HOMER Pro model incorporates these load variations to analyze the system's performance, ensuring optimal generator scheduling, solar power integration, and blackout risk mitigation. The simulation results help determine the best operational strategy, minimizing fuel consumption and financial losses while maintaining system reliability.

3.4.3 Simulating Operational Scenarios

In the simulation of operational scenarios using HOMER Pro, several key operating conditions were modeled to reflect real-world hybrid energy system behavior. A operational mode was analyzed where only the grid supplies the load, without contributions from solar or generators.

This is the simplest mode and is generally stable but does not utilize the potential cost savings or environmental benefits that come with renewable integration. In the scenario, when the grid is unavailable, the generator becomes the primary energy source.

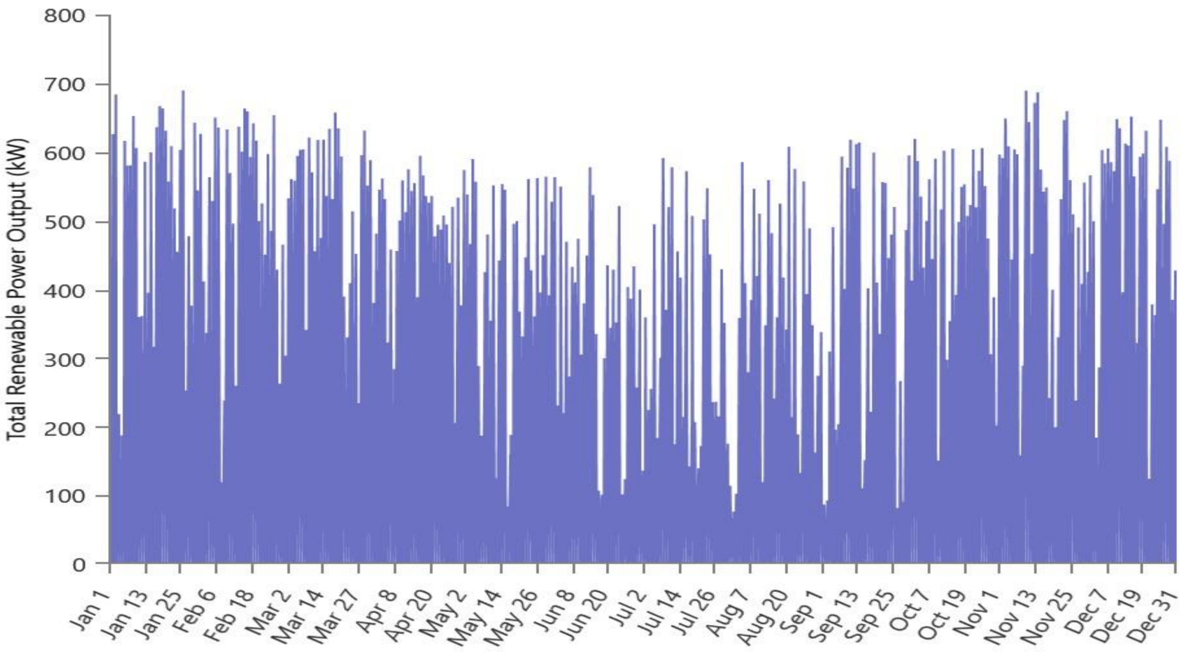

Figure 3.9: Simulation of Solar Output with Homer Pro based on GI in 2024

The graph (figure-3.9) represents the total renewable power output in kW over a one-year period. The x-axis shows dates from January 1 to December 31, indicating daily data throughout the year. The y-axis represents the power output, ranging from 0 to 800 kW. Output peaks frequently above 600 kW, with noticeable dips.

Here, solar PV can still operate alongside the generator using a grid-tied inverter. However, operational challenges emerge due to the high solar irradiation (GI) during sunny periods, the load on the generator drops significantly. If the generator is not sufficiently loaded, it becomes unstable and trips frequently, leading to reliability concerns and potential energy shortages.

To address these issues, an optimization strategy was applied when operating the solar and generator together. The key optimization rule enforced that the generator must maintain at least 30% of its rated capacity during operation to ensure stable performance and prevent frequent tripping. If the solar generation is too high relative to the load (causing the generator to fall below 30% loading), the solar power is curtailed as needed. This controlled curtailment of solar ensures generator stability while still maximizing solar utilization where possible. Through this optimization approach, the system balances reliability with renewable integration.

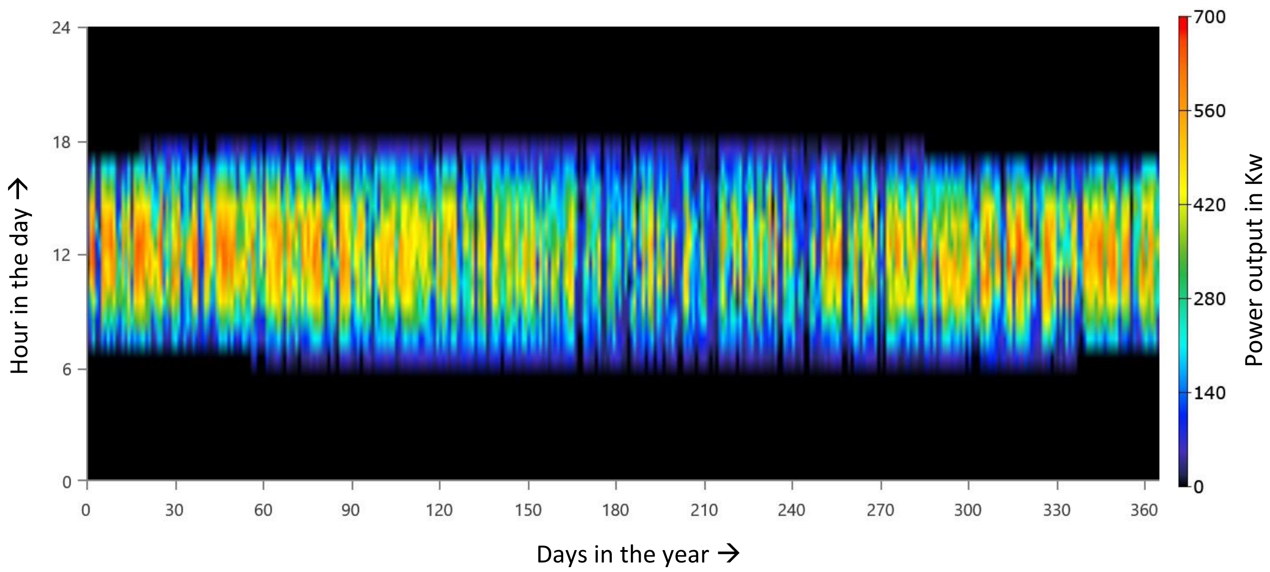

Figure 3.10: Solar Output of Synergy Optimization

In figure-3.10, X-axis represents Days in the year from 0 to 365 roughly one year. Y-axis represents hour in the day" from 0 to 24 hours. Color represents power output in kW. Black/dark areas indicates no power of 0 kW. Blue areas means low power upto~140 kW. Green to yellow areas represents medium power (~280 to 420 kW).Orange to red areas indicates high power up to 700 kW. Nighttime 6 PM to 6 AM is black meaning no solar production, as expected. In the middle of the day around 6 AM to 6 PM shows higher power output, especially around noon.

HOMER Pro simulations can optimize the operational strategy to avoid blackout by dynamically balancing solar penetration and generator output. This can evaluate these conditions and suggest optimal configurations, including potential adjustments in generator dispatch strategy while maintaining power reliability.

CHAPTER 4: COMPARATIVE ANALYSIS AND RESULT FORMULATION

4.1 MATHEMATICAL MODEL VALIDATION

The proposed mathematical model was designed to optimize the synergy between solar PV and generator power while maintaining system reliability under intermittent stochastic conditions. The model successfully,

- Ensured minimum generator loading (30%) to prevent tripping.
- Optimized power sharing between solar and generator to minimize blackout.

The model is implemented under different scenarios, confirming that without optimization, frequent blackouts occurred when solar irradiance was high and load was low, causing the generator to trip.

4.2 ENERGY CONTRIBUTION

The comparison between the optimized and non-optimized system shows clear improvements when optimization is applied. With optimization, the total energy generated increased to 18,316,765 kWh compared to 17,744,558 kWh without it, marking a 3.2% increase. This boost in generation is largely attributed to the integration of Photo Voltaic (PV) energy, which contributed 1,079,971 kWh. In the non-optimized case, no PV contribution was present, meaning the system relied solely on generator power. The addition of solar energy not only increased overall generation but also diversified the energy sources, making the system less dependent on generators alone.

Table-4.1: Energy Contribution Result from HOMER Pro

Parameter	With Optimization	Without Optimization
Total Energy Generated (kWh)	18,316,765	17,744,558
PV Energy Contribution (kWh)	1,079,971	0
Generator Energy Contribution (kWh)	17,236,794	17,744,558
Total Energy Consumed (kWh)	18,316,765	17,744,558

As a result of the optimization, the generator's energy contribution decreased from 17,744,558 kWh to 17,236,794 kWh, representing a 2.9% reduction. This reduction is significant because it suggests a lower operational burden on generators, which could lead to less fuel consumption, lower maintenance needs, and decreased emissions. Additionally, the total energy consumed matches the total energy generated in both scenarios, but the optimized system provides slightly more energy, possibly reducing the likelihood of energy shortages or unmet demand.

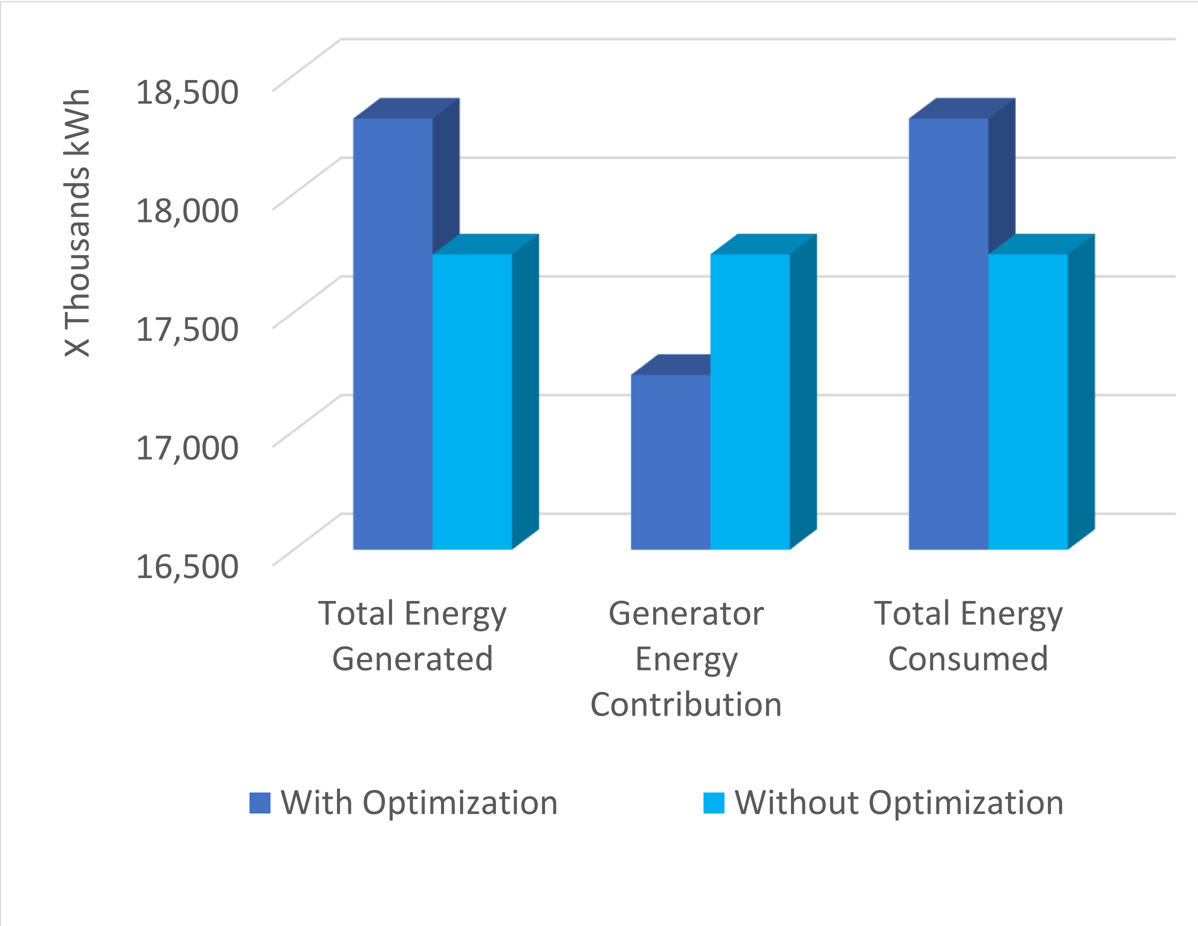

Figure-4.1: System Energy Contribution

This indicates energy metrics with and without optimization. It highlights that optimization leads to a higher total energy generation and consumption, indicating more efficient energy utilization. The generator energy contribution is reduced with optimization that shift toward more sustainable energy sources. Overall, optimization enhances system sustainability by incorporating renewable energy sources.

To calculate total system efficiency, we use the formula, Efficiency (%) = (Total Electrical Output / Total Fuel Energy Input) × 100 (4.1)

With Optimization:

- Total Electrical Output: 18,316,765 kWh
- Total Fuel Energy Input: 44,068,842 kWh
- Efficiency: (18,316,765 / 44,068,842) × 100 = 41.6%

Without Optimization:

- Total Electrical Output: 17,744,558 kWh
- Total Fuel Energy Input: 45,271,277 kWh
- Efficiency: (17,744,558 / 45,271,277) × 100 = 39.2% (System Efficiency Improvement)

Percentage Increase = (41.6 - 39.2) % = 2.4%

The simulation result indicates system efficiency increased by 2.4%, meaning the optimization led to better energy utilization and reduced fuel dependency.

4.3 SYSTEM RESELIENCE ANALYSIS

Ensuring a stable power supply is vital for any energy system. System resilience is analyzed by measuring capacity shortage and availability percentage. A reliable system reduces dependency on backup power sources and minimizes economic losses due to power outages.

Table-4.2: Resilience Result from HOMER Pro

Metric	Without Optimization	With Optimization	Impact
Capacity Shortage (GWhr)	3.811	3.503	8.10%

Capacity shortage indicates how much and to what extent the system fails to meet demand. Reducing these factors is essential to improving the overall dependability of the power supply. The introduction of PV significantly reduces shortages by supplementing generator output.

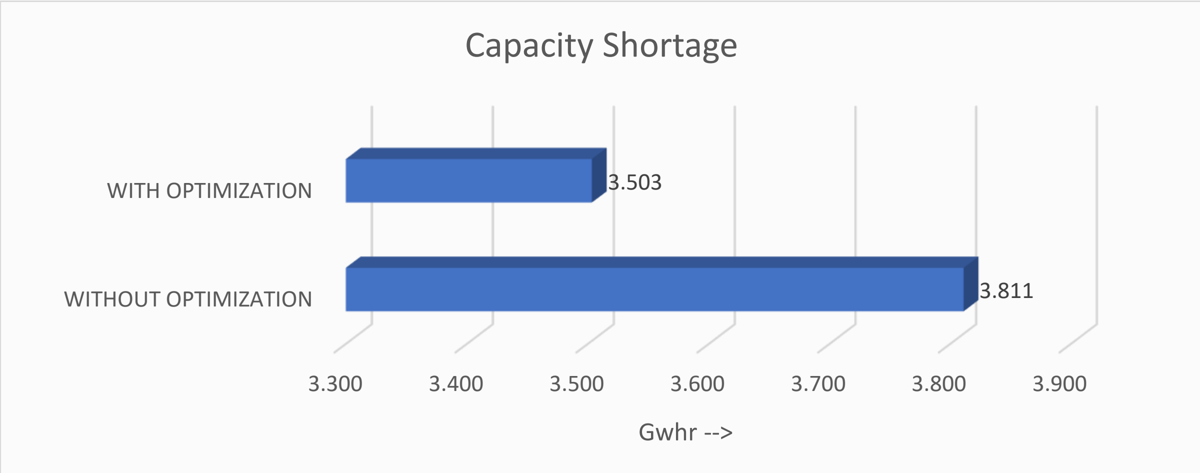

Figure-4.2: System Resilience Analysis

In simulation the Capacity Shortage with optimization is 3,503,327 kWh/yr & and without optimization the Capacity Shortage is 3,811,110 kWh/yr. It indicates the optimization reduces capacity shortage by 8.1%, enhancing reliability. Availability percentage measures the proportion of time the system successfully supplies power. A higher availability percentage indicates a more stable and efficient energy system. The integration of PV leads to a noticeable improvement in system availability, ensuring a more consistent power supply.

4.4 SYSTEM RELIABILITY ANALYSIS

Unmet load directly affects the reliability of a power system by indicating how often and how severely the system fails to supply the energy needed by users. A high unmet load means the system cannot meet demand during certain periods whether due to limited generation, insufficient power supply or external disruptions which reduces the system's ability to cope with stress or recover from disturbances. This affects the reliability as the system becomes more prone to outages, service interruptions and slow recovery after crises.

When unmet load is reduced, the reliability of the power system improves significantly. Lower unmet load means the system can supply electricity more consistently, even under adverse conditions. It ensures greater reliability for critical infrastructure, improves user confidence and reduces the need for emergency responses like load shedding or generator use. Additionally, a system with low unmet load is better prepared to absorb shocks, maintain stability and recover quickly from failures, making it more robust and dependable.

Table-4.3: Reliability Result from HOMER Pro

Metric	Without Optimization	With Optimization
Unmet Load (kWhr)	1,960,032	1,387,825

The data indicates that after optimization integrating solar energy into the power system significantly improves its performance by reducing the annual unmet load from 1,960,032 kWh to 1,387,825 kWh, a reduction of 572,207 kWh. Unmet load represents the portion of electricity demand that the system fails to supply, so a decrease in this value signifies a notable improvement in system reliability and availability. With PV in place, the system can meet more demand, particularly during daylight hours when solar generation is at its peak. This leads to increase availability of electricity, meaning fewer power shortages, improved service quality and reduced reliance on backup sources like diesel generators. Additionally, it enhances energy security and contributes to environmental sustainability by displacing a portion of fossil fuel-based generation.

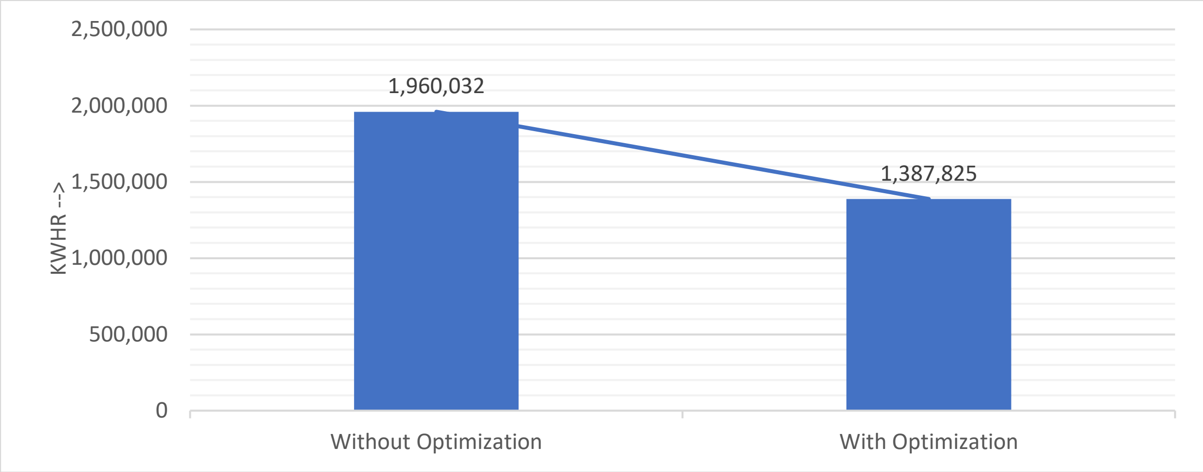

Figure-4.3: System Reliability Analysis

The reduction of unmet load from 1,960,032 kWh to 1,387,825 kWh through optimization an improvement of 29.2% positively impacts the reliability of the power system. By minimizing unmet load, optimization ensures that a larger portion of energy demand is reliably met, even under challenging conditions such as peak usage, equipment failures or fuel supply disruptions. This enhances the system's ability to maintain continuous operation during disturbances, which is a key aspect of reliability. Furthermore, with fewer shortages, the system experiences less stress and can recover more quickly from disruptions. The reduction in unmet load through optimization strengthens the power system's capacity to adapt to and recover from extreme events, thereby enhancing its reliability.

4.5 SENSITIVITY ANALYSIS

Sensitivity analysis is used to assess how changes in input variables affect the output or overall performance of a system or model. It helps to identify the parameters that have the most significant impact allowing researchers and engineers to focus on critical factors that influence system behavior. This method is especially important in complex systems like hybrid energy networks where multiple variables like load demand, fuel cost or solar irradiance interact dynamically.

4.5.1 Sensitivity Analysis for Variable Solar Irradiance Dynamics

Sensitivity analysis for variable solar irradiance dynamics reveals that fluctuations in solar input significantly influence multiple operational aspects of a hybrid energy system. Variations in irradiance directly impact PV utilization often leading to increased curtailment during periods of low demand or high solar output especially in the absence of storage. Consequently, the frequency of curtailment events highlighting the importance of adaptive control strategies to manage solar variability effectively.

Table-4.4: Variable Solar Irradiance Dynamics Sensitivity Analysis

Solar Irradiance Variation	**PV Output**	**Generator Load Share**	**Curtailment of PV Power**	**Generator Mode**
-30%	Very Low	High (close to 100%)	None	Primary supply
-20%	Low	High	None	Continuous
-10%	Moderate	Medium-high	Low	Partial
+0% (Nominal)	Balanced	Balanced	Minimal	Synergistic
+10%	High	Low	Moderate	Curtailment starts if gen <30%
+20%	Very High	Very Low	High	Curtailment frequent
+30%	Excess	Below 30%	Severe	Curtailment mandatory

The table outlines how variations in solar irradiance affect the operation of a hybrid energy system, particularly the distribution of load between PV output and generator, as well as the extent of PV power curtailment. At irradiance levels below baseline, PV output is low to moderate, requiring the generator to supply most of the load operating in either primary, continuous or partial modes with little to no curtailment. At nominal irradiance (0%), the system achieves a balanced synergy between PV and generator, with minimal curtailment. As irradiance increases above nominal levels (+10% to +30%), PV output becomes high to excessive.

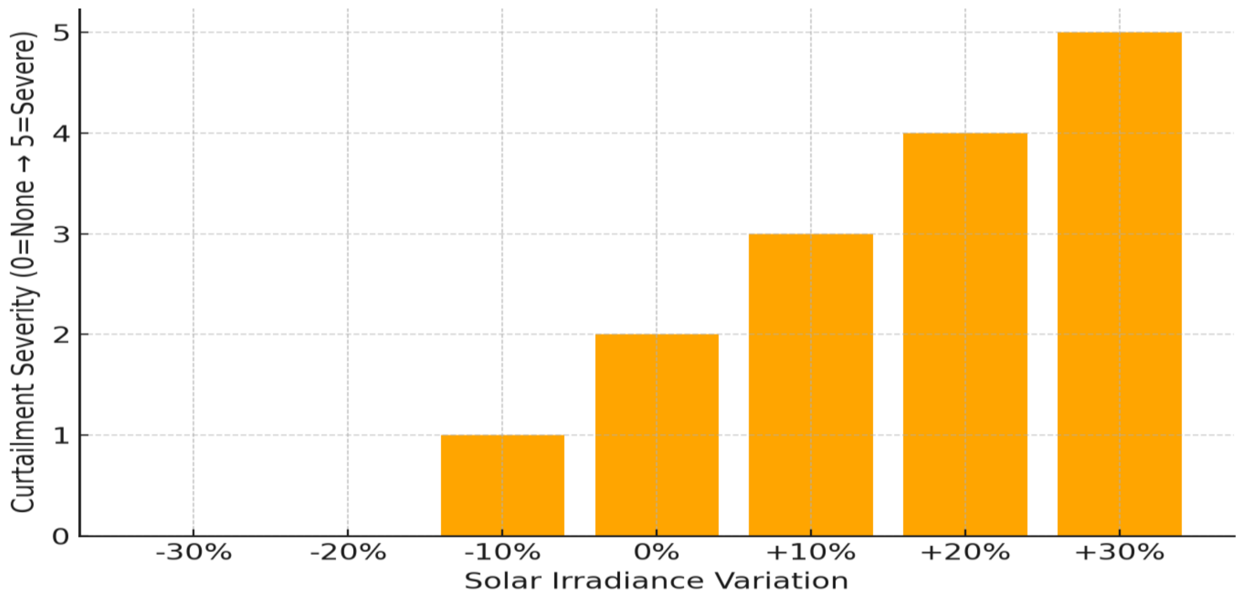

Figure-4.4: Curtailment Severity in Response to Varying Solar Irradiance

The bar chart depicts the impact of solar irradiance variation in X-axis and curtailment severity in Y-axis, where curtailment severity ranges from 0 (None) to 5 (Severe). As the solar irradiance increases from -30% to +30%, the severity of curtailment also increases. At negative irradiance variations i.e., -30% and -20% no curtailment occurs indicating that the system is capable of fully utilizing the available solar energy under reduced solar conditions.

However, as irradiance rises above the baseline (0%) curtailment severity progressively increases reaching the maximum level of 5 at +30% variation. This suggests that in high solar conditions excess energy cannot be accommodated likely due to operational constraints such as the generator's minimum loading limit necessitating curtailment to maintain system stability.

This bar chart illustrates the relationship between Solar Irradiance Variation on X-axis) and Curtailment Severity on Y-axis. It shows the percentage change in solar irradiance relative to a baseline ranges from -30% to +30% in increments of 10%. Negative values (-30%, -20%, -10%) represent reduced solar irradiance. Positive values (+10%, +20%, +30%) represent increased solar irradiance. 0% indicates the base line on irradiance. The Y axis quantifies the severity of solar power curtailment, on a scale from 0 (None) to 5 (Severe). Higher values indicate more severe curtailment due to system limitations or constraints.

The chart shows that as solar irradiance increases beyond the baseline (0%), curtailment severity increases. At -30% and -20%, there is no curtailment meaning the system can absorb all the available solar energy when irradiance is low. From -10% onward, curtailment begins and progressively worsens, peaking at +30% irradiance with a severity level of 5. This trend implies that excess solar energy according to high irradiance leading to curtailment due to generator minimum loading constraints.

4.5.2 Sensitivity Analysis for Variable Load Dynamics

Variable load dynamics significantly influence the performance and coordination of generator and PV contributions in a hybrid energy system. As load increases or decreases, the system must continuously adjust the power share between the generator and PV. During high-load periods, the generator takes on a greater share. Conversely, during low-load conditions especially when solar irradiance is high PV output may exceed demand, forcing curtailment to maintain generator operation above its minimum threshold.

Table-4.5: Variable Load Dynamics Sensitivity Analysis

Load Variation	Load Demand (MW)	Gen Load %	PV Share	Curtailment of PV Power	Risk of Blackout
-60%	0.4	<30%	High	Curtailment	Low
-40%	0.6	~30%	High	Close to Curtailment	Low
-20%	0.8	40%	High	Close to Curtailment	Low
+0% (Base)	1.0	50–60%	High	No	None
+20%	1.2	70%	High	No	None
+40%	1.4	~85%	High	No	Low
+60%	1.6	~100%	High	No	Low

The table highlights how varying load demand affects generator loading, PV power contribution, curtailment, and blackout risk in a hybrid system. Under reduced load conditions -60% to -20%, the total demand drops significantly 0.4MW to 0.8 MW causing the generator load to fall below or near its minimum operational threshold (30%). Although PV share remains high in these scenarios, curtailment becomes necessary to prevent generator underloading, especially when the generator must remain online. Despite these challenges, the risk of blackout remains low due to excess available power.

As load increases from the base level 1.0 MW to +60% 1.6 MW, the generator progressively takes on a higher load share rising from 50% to 60% up to full capacity. In these higher load conditions, PV output continues to contribute substantially without requiring curtailment, since the overall demand supports full solar utilization.

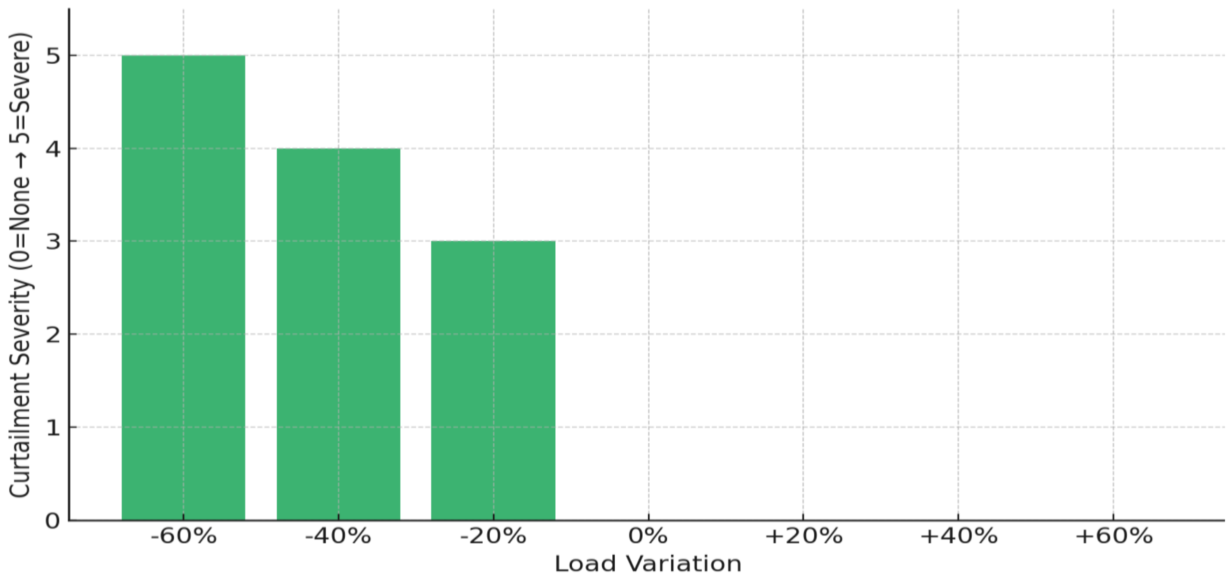

Figure-4.5: Curtailment Severity as Load Varies in the System.

The chart indicates that curtailment severity is highest during extreme load reductions and gradually decreases as load approaches or exceeds the base level, with no curtailment required at or above 0% load variation

The bar chart illustrates the relationship between Load Variation in X-axis and Curtailment Severity Y-axis in a hybrid energy system. It represents changes in load demand relative to the base level (0%). & ranges from -60% meaning significant load reduction to +60% which is significant load increase. Negative values indicate decreased load, while positive values represent increased demand. It also indicates the extent of PV power curtailment, scaled from 0 (None) to 5 (Severe). Higher values mean more solar energy had to be curtailed due to system constraints like low load or generator minimum loading limits.

At -60% to -20% load variation, curtailment severity is high from level 5 to 3, since low demand forces excess PV energy to be curtailed to prevent generator underloading. At 0% and above, curtailment severity drops to 0, indicating that the full solar output can be utilized efficiently as demand increases. This graph clearly shows that curtailment is primarily a concern under low-load conditions, emphasizing the need for dynamic load management.

4.6 FINANCIAL ANALYSIS

A hybrid energy system must be financially viable to ensure long-term sustainability. This section evaluates the cost of blackouts, net present cost (NPC) and the levelized cost of energy (LCOE) to determine the economic impact of PV integration.

4.6.1 Cost of Blackouts

Power outages can lead to substantial financial losses, particularly for businesses and industries. Reducing the frequency and duration of blackout minimizes economic disruptions. Synergy optimization in the system decreases the unmet load, lowering the overall cost of power shortages. To quantify the financial impact of blackout, following formula is used,

$$\text{Cost of Blackouts} = \text{Unmet Load} \times \text{Value of Lost Load (VoLL)} \qquad (4.2)$$

Here the considerations are,

- VoLL (Value of Lost Load): Estimated at $0.50/kWh (varies by industry).
- Unmet Load With optimization: 1,387,825 kWh/yr
- Unmet Load Without optimization: 1,960,032 kWh/yr

By Calculating the Cost of Blackouts,

- With optimization: 1,387,825 x 0.5= 693,912.50 USD/year
- Without optimization: 1,960,032 x 0.5= 980,016.00 USD/year

Savings while optimization: 693,912.50-980,016.00 = 286,103.50USD/year

Savings % = (Savings with optimization / Cost Without optimization) × 100 (4.3)

Substituting the values,

(286,103.50 / 980,016.00) × 100

= 29.2% (reduction)

These results demonstrate that system optimization significantly lowers the economic losses associated with blackouts, providing both financial and operational benefits. The optimization in the system decreases the unmet load, lowering the overall cost of power shortages. A reduction in unmet load suggests lower economic losses associated with power outages.

4.6.2 Total Net Present Cost (NPC)

The Net Present Cost (NPC) reflects the total lifetime cost of the energy system, including capital, operating, and replacement costs. A lower NPC indicates a more cost-effective system. The optimization results a decrease in NPC, proving its financial benefit in the long run.

- With Optimization: $58,958,620
- Without Optimization: $60,536,240
- Savings: $1,577,620 (2.6% lower cost with Optimization).

4.6.3 Levelized Cost of Energy (LCOE)

LCOE is a critical metric that measures the cost of generating one unit of electricity over the system's lifetime. A lower LCOE indicates a more economical power generation method. It reduces LCOE, making the system more financially feasible and sustainable.

- With Optimization: $0.249/kWh
- Without Optimization: $0.264/kWh
- Reduction: LCOE decreased by 5.7%, making energy more cost-effective.

HOMER's Financial analysis estimated the financial losses due to blackout and how much the proposed optimization strategy reduces downtime costs. The proposed algorithm significantly reduced financial losses, demonstrating its ability to enhance the economic viability of industrial energy systems. By optimizing power distribution and minimizing generator tripping, the algorithm ensures a more stable and reliable power supply, ultimately reducing the financial impact of blackouts and demonstrating its effectiveness for industrial applications.

4.7 ENVIRONMENTAL EFFECT ANALYSIS

Emission comparison highlights the environmental benefits while optimizing the system. The reduction in carbon dioxide emissions contributes to climate change mitigation. Additionally, lower levels of nitrogen oxides and sulfur dioxide help improve air quality and reduce environmental harm. By decreasing reliance on fossil fuels, the system transitions toward a more sustainable and eco-friendly energy solution.

Table-4.6: Green House Effect Analysis Simulation

Pollutant	**With optimization (kg/yr)**	**Without Optimization (kg/yr)**	**Reduction (%)**
Carbon Dioxide	11,796,362	12,118,231	2.7%
Carbon Monoxide	29,111	29,905	2.7%
Unburned Hydrocarbons	2,329	2,392	2.6%
Particulate Matter	4,523	4,647	2.7%
Sulfur Dioxide	29,361	30,162	2.7%
Nitrogen Oxides	111,023	114,052	2.7%

The optimization process led to a measurable reduction in the emission levels of all listed pollutants. Carbon Dioxide emissions decreased from 12,118,231 kg/year to 11,796,362 kg/year, a reduction of approximately 321,869 kg/year or 2.7%. Similar percentage reductions are observed across other pollutants. Carbon Monoxide reduced by 794 kg/year, Unburned Hydrocarbons by 63 kg/year, Particulate Matter by 124 kg/year, Sulfur Dioxide by 801 kg/year, and Nitrogen Oxides by 3,029 kg/year. These consistent reductions, ranging around 2.6–2.7%, indicate that the optimization mechanism effectively enhances environmental performance by minimizing harmful emissions across various pollutant categories.

The hybrid system significantly lowers pollutants, leading to better environmental and public health outcomes. this research supports national and global efforts to reduce Green House Gas (GHG) emissions while ensuring energy resilience in industrial applications. By improving the reliability of hybrid systems, industries can lower their carbon footprint and move toward sustainable energy solutions. This aligns with policies aimed at reducing fossil fuel dependence, promoting renewable energy and minimizing the environmental impact of industrial power usage, making a meaningful contribution to combating climate change.

CHAPTER 5: DISCUSSION & RECOMMENDATION

5.1 DISCUSSION

This project explores the Synergy Optimization Algorithm of Heterogeneous Hybrid Energy Architecture to Enhance Resilience and Reliability in an Intermittent Stochastic Power Network. The research is centered on the integration of solar power, grid electricity and diesel generators in an industrial setting, ensuring a resilient and optimized power supply even during grid failures. Given the stochastic nature of renewable energy, particularly solar power and the operational constraints of generators maintaining a stable and efficient hybrid system is a key challenge.

The study identifies that solar intermittency, lack of energy storage and minimum generator loading constraints can lead to blackout risks, especially during off-grid operation. Since solar inverters require a reference power source, at least one generator must remain active with the grid to prevent a complete system shutdown. The research further examines interlocking and synchronization mechanisms, ensuring that power transitions occur smoothly without damaging electrical components.

To simulate the hybrid system's performance and economic impact, the research employs HOMER Pro, a well-established energy modeling tool. An important aspect of the study is the evaluation of financial impact, which helps in understanding the economic feasibility of the proposed optimization strategy. The project also designs the solar power integration, maximizing renewable energy utilization while maintaining system stability.

By Summarizing the key performance metrics help evaluate the overall effectiveness of the hybrid energy system. The inclusion of PV led to noticeable improvements in capacity shortage, unmet load, efficiency and financial savings. By reducing dependency on diesel generators, the system achieved a **2.6%** reduction in Net Present Cost (NPC) and a **5.7%** decrease in Levelized Cost of Energy (LCOE). These metrics confirm that optimization enhances both economic and operational efficiency.

Table-5.1: Summarized Key Matrices Comparison

Metric	With Optimization	Without Optimization	Improvement
Capacity Shortage (kWh/yr)	3,503,327	3,811,110	8.1%
Unmet Load (kWh/yr)	1,387,825	1,960,032	29.2%
System Efficiency (%)	41.6	39.2	6.1%
Net Present Cost (NPC) ($)	58,958,620	60,536,240	2.6%
LCOE ($/kWh)	0.249	0.264	5.7%

Energy generation and consumption patterns indicate how effectively the hybrid system meets demand. With optimization, the PV system contributed 1,079,971 kWh, offsetting fossil fuel usage. This demonstrates that even a moderate share of renewable energy can significantly lower generator dependency and improve sustainability.

The research highlights that synergy optimization among grid, solar and generators can significantly improve the resilience and efficiency of the power network. The findings demonstrate that strategic generator scheduling, real-time load balancing and adaptive system operation can reduce fuel consumption, prevent generator underloading and mitigate blackout risks. Overall, this research provides valuable insights into hybrid energy system management for industrial applications, offering an optimized approach to balancing energy reliability, operational efficiency and economic sustainability. The findings contribute to the ongoing efforts of enhancing energy resilience in Bangladesh, supporting industrial growth while promoting renewable energy integration.

5.1.1 Technological Impact

This project introduces advanced optimization strategies for hybrid energy systems, significantly impacting the technological landscape of industrial power management. By integrating solar energy, grid power and diesel generators under an optimized control framework, the research enhances system resilience, reliability and operational efficiency.

Another critical technological aspect is simulation-based financial impact assessment using HOMER Pro, which provides a data-driven approach to power system design and economic analysis. This enhances decision making for industries looking to integrate renewable energy without compromising reliability. Furthermore, the study also incorporates interlocking and synchronization mechanisms to prevent unsynchronized breaker closures, thereby reducing the risk of equipment failure and power system instability.

5.1.2 Financial Impact

The findings of this project have significant financial implications, particularly for industrial energy users relying on hybrid energy systems. By optimizing the synergy between solar power, grid electricity and diesel generators, the research aims to reduce operational costs and prevent financial losses from blackout.

Unplanned power outages in industries can lead to substantial production losses, equipment damage and supply chain disruptions. By implementing an optimized hybrid system with proper generator loading, interlocking mechanisms and energy management, this research helps mitigate blackout induced financial risks. The HOMER Pro simulation results provide insights into potential cost savings for industries adopting such optimized hybrid energy models.

5.1.3 Environmental Effect

The system optimization contributes to meaningful environmental improvements by reducing key pollutant emissions. Across the board, emissions of carbon dioxide, carbon monoxide, sulfur dioxide and nitrogen oxides each decreased by 2.7%, while unburned hydrocarbons were reduced by 2.6%. Although the percentage reductions may seem modest, they represent substantial absolute decreases in pollutant output over a year, particularly for high-volume emissions like carbon dioxide and nitrogen oxides. These reductions not only reflect improved energy efficiency but also indicate a shift toward cleaner and more sustainable power system operations. By minimizing the release of harmful gases, optimization enhances air quality and helps mitigate the environmental and health impacts of power generation, underscoring its value as a key strategy in both emissions control and climate resilience efforts.

5.2 RECOMMENDATION

To ensure a stable, resilient and cost-effective hybrid energy system, industries must adopt an optimized energy management strategy that dynamically distributes power between the grid, generators and solar resources. One critical aspect is enforcing minimum generator loading threshold of 30%, preventing generator underloading and ensuring uninterrupted solar power utilization in off-grid conditions. Additionally proper synchronization and interlocking mechanisms should be implemented to prevent unsynchronized breaker closures, which could lead to severe electrical faults and system instability.

To improve system reliability, automated load prioritization should be employed to maintain critical industrial processes even during power shortages. Advanced fault detection mechanisms, such as AI-driven predictive maintenance and real-time monitoring, can further minimize the risks of voltage fluctuations, harmonics and cascading failures.

To support industrial hybrid energy adoption, government policies and financial incentives such as tax benefits, subsidies and low-interest financing should be introduced to encourage investment in sustainable energy solutions. These strategies will not only enhance industrial power reliability but also contribute to the national goal of a resilient and optimized hybrid energy infrastructure, reducing dependence on fossil fuels and help to improve long-term economic sustainability.

CHAPTER 6: CONCLUSION

6.1 CONCLUSION

This project introduces a Synergy Optimization Algorithm designed to improve the resilience and reliability of Heterogeneous Hybrid Energy Systems operating under intermittent and stochastic conditions. The study addresses a critical challenge in hybrid energy networks the instability caused by generator tripping due to fluctuating solar power and low-load conditions. Through mathematical modeling and planned HOMER Pro simulations, the research provides a structured approach to minimizing blackouts, optimizing power flow and reducing financial losses. The proposed optimization strategy demonstrates several key benefits,

- By maintaining generator load above critical thresholds, the algorithm prevents unnecessary shutdowns and blackouts that enhance system reliability by 29.1%.
- The system dynamically balances solar PV and generator power, ensuring optimal operation that reduces capacity shortage meaning resilience increases by 8.1%.
- Economically, the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) are reduced by 2.7% and 5.7% respectively, leading to long-term cost savings.
- Optimization lowers fuel consumption and results in measurable reductions in harmful emissions such as CO_2, CO, NO_x, SO_2 and unburned hydrocarbons. All decreasing by approximately 2.6–2.7% contributes to reduce Green House Effect.

This research presents a synergy optimization algorithm to enhance the resilience and reliability of a heterogeneous hybrid energy system in an industrial setup. By integrating grid power, diesel generators and a solar PV system the proposed architecture ensures continuous power supply, even under grid outages and stochastic power fluctuations. A key feature of this system is the intelligent synchronization and interlocking mechanism, which prevents unsafe switching operations and ensures smooth transitions between power sources. Additionally, bus couplers (BC) and tie breakers (TB) are incorporated to facilitate dynamic power routing, preventing overloads and ensuring balanced load distribution.

A critical challenge addressed in this study is the blackout risk associated with grid failures, which can cause solar inverters to shut down if no generator is running. The research mitigates this issue by ensuring at least one generator remains operational with the grid and during off-grid conditions, thereby maintaining the necessary voltage and frequency reference for solar

PV operation. Moreover, the system implements a priority-based load-shedding strategy, disconnecting non-priority loads (1.5MW) when power constraints arise, ensuring that critical industrial processes (1.0MW) remain uninterrupted.

To enhance system reliability, fault prevention measures, including fast-acting circuit breakers, overcurrent protection, and automated isolation mechanisms, are integrated. The busbar system is designed to handle peak current loads efficiently, minimizing the risk of overheating and voltage drops. The research also ensures that generator loading is maintained above 30%, preventing tripping due to underloading and enabling optimized energy utilization.

The financial impact is being analyzed using HOMER Pro simulations, quantifying economic impacts and efficiency improvements under different operational scenarios. The results of this study will contribute to the development of intelligent hybrid energy management strategies, ensuring cost-effective, resilient and sustainable industrial power solutions. The proposed approach provides a scalable framework that can be adapted to similar industrial applications, addressing the challenges posed by intermittent power sources and grid instabilities.

6.2 RESEARCH LIMITATION

The study relies on simulation-based analysis using HOMER Pro, which, while effective, may not fully capture real-world uncertainties such as sudden equipment failures, extreme weather conditions or unforeseen power demand spikes. The accuracy of the financial impact estimation depends on assumptions of industry-specific factors, which may vary in actual operational environments. The study primarily evaluates system performance based on predefined load patterns without considering adaptive real time conditions.

6.3 FUTURE SCOPE OF RESEARCH

While the study establishes a strong foundation for hybrid system optimization, future research should focus on real-world validation through hardware-in-the-loop (HIL) testing. AI based predictive control and the integration of energy storage solutions can further enhance system performance.

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