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# DESIGN, OPTIMIZATION, AND PERFORMANCE EVALUATION OF HYBRID MICROGRID SYSTEMS: A COMPREHENSIVE STUDY ON ENERGY MANAGEMENT AND RENEWABLE INTEGRATION

Hamza Munir [1], Dr. Tahir Izhar*[2]

[1]*Department of Engineering and Technology, Superior university,Lahore.*
[2]*Department of Engineering and Technology, Superior university , Lahore*
[1]*hamzah.hh438@gmail.com*, [2]*tizhar@gmail.com*

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Corresponding Author: *
Hamza Munir*

## Abstract

*As sustainability and de-carbonization issues are getting more and more important all over the world, New energy management systems have to be developed for electrical networks. The powered smart microgrids that use a mix of renewable energy sources are turning out to be one of the ways to power generation that is stable, reliable, and eco-friendly. However, the major difficulties are balancing supply and demand and keeping costs down in real-time because the resources come and go in an unpredictable manner. The research has been done for an energy management scheme for a hybrid microgrid that consists of solar, wind, and battery storage by both theoretical and simulation-based analyses. The proposed control frame uses intelligent techniques like model predictive control, fuzzy logic control, and artificial neural networks for forecasting, scheduling, and optimization of the grid. The MATLAB/Simulink and HOMER Pro simulation environments have been utilized to validate the model proposed under various operational scenarios. The findings indicate that the implementation of an adaptive energy management system can lead to a significant reduction in operational costs, increased use of renewables, and better quality of power. The research also helps to further establish the conceptual framework of the development of microgrids that are eco-friendly and scalable to both rural electrification and urban load support in Pakistan and other developing regions.*

# INTRODUCTION

## 1.1 Background

The global energy landscape is changing really fast as countries are looking for clean and more sustainable power sources to fulfill their increasing electricity demand. Conventional electric power grids, which were majorly dependent on fossil fuels, are now dealing with serious problems like high transmission losses, and limited reliability, plus are the major contributor of greenhouse gases. Disrespecting these problems has resulted in the search for power generation methods that are characterized as renewables, stable, and low-carbon. By way of combining renewable energy generation, storage systems, and advanced control algorithms to manage energy at the local level, smart microgrids provide an exceptional solution. A microgrid can either work as an independent island system or share the main grid. Nevertheless, its performance to a great extent depends on the presence of an effective energy management system (EMS) which ensures that different power sources and storage devices operate in sync with each other at very short intervals.

## 1.2 Define and Explain Microgrid

A localized energy system that can be operated independently or coupled with the main power grid is a microgrid. It combines multiple electricity production (such as solar panels, wind turbines, diesel generators) energy storage (such as batteries) and loads (built in homes, buildings, industries) to one, manageable system.

## 1.3 Distributed Energy Resources (DERs)

Renewable: solar PV, wind turbines, small hydro, biomass.Traditional: diesel / gas generators.Combined heat and power (CHP) or fuel cells.

### 1.3.1 Energy Storage Systems (ESS):

Lithium-ion batteries, flow batteries.Thermal storage.Flywheel storage (mechanical).

### 1.3.2 Control System:

Intelligent controllers, sensors and real-time monitoring and balancing/demand/supply software.Mechanizes steady voltage and frequency and power quality.

**Loads:**Residential centers, business centers, manufacturing activity, hospitals or military commands.The priority of loads can be given (critical and non-critical).

**Point of Common Coupling (PCC):** The point through which the microgrid and the main grid interact.Allows grid-connected and islanded mode switching.

### 1.4 Microgrid Working

**Normal Conditions (Grid Connected Mode):** The microgrid receives exchange of electricity with the main grid.The excess renewable energy may be injected to the grid.Grid strengthens microgrid when it is in demand.

**Outage (Island Mode):** The microgrid is separated out of the main grid and operates on its own.Storage + local generation provides certain supply.Power-sensitive loads (hospitals, emergency centers) have precedence power.

**Smart Management:** Good control systems maximize energy consumption.

### 1.5 Opportunities of Microgrids

Energy Resiliency: Maintains supply when there is a blackout. Renewable Integration: Practices maximum utilization of solar, wind and other clean energy. Cost Saving: Saves energy bills due to the ability of generating and storing local electricity. Grid Supporting: Supports to stabilize the main grid by balancing the variations. Environmental Advantages: Reduces carbon emission by means of using clean energy.

### 1.6 Kinds of Microgrids

**Off-Grid Microgrids/Remote Microgrids:** Unlinked to the central grid (applied in islands, rural or developing areas).

**Grid-Connected Microgrids:** be able to operate with the utility grid but be able to disconnect.

**Hybrid Microgrids:** Employ a diverse supply (renewable + conventional + storage).

**Real life examples**

**University Campuses**: A large number of US campuses operate microgrids to secure power supply and reduce expenditures.

**Figure 1. Microgrid Block Diagram**

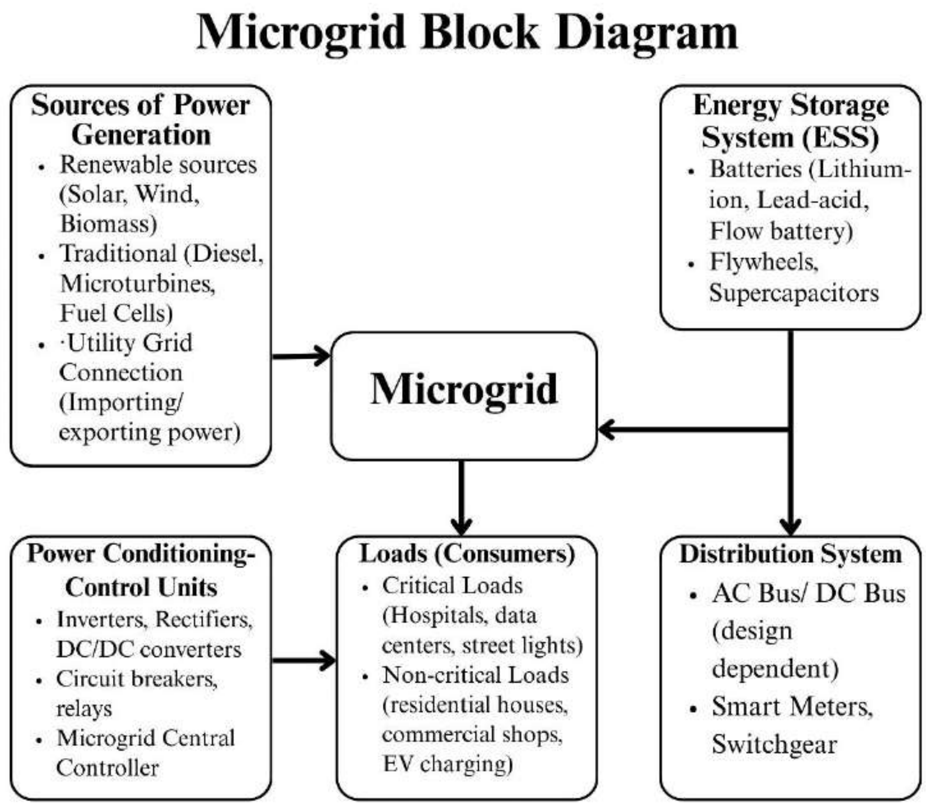
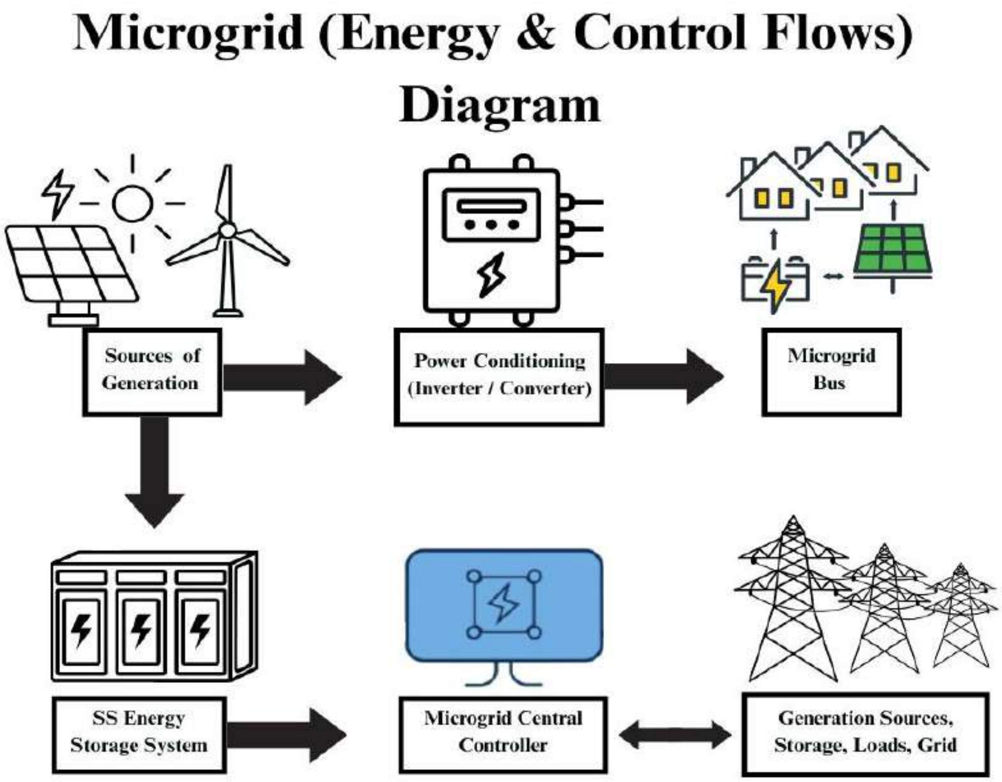


**Figure 2. Microgrid (Energy & Control Flows) Flow Diagram**

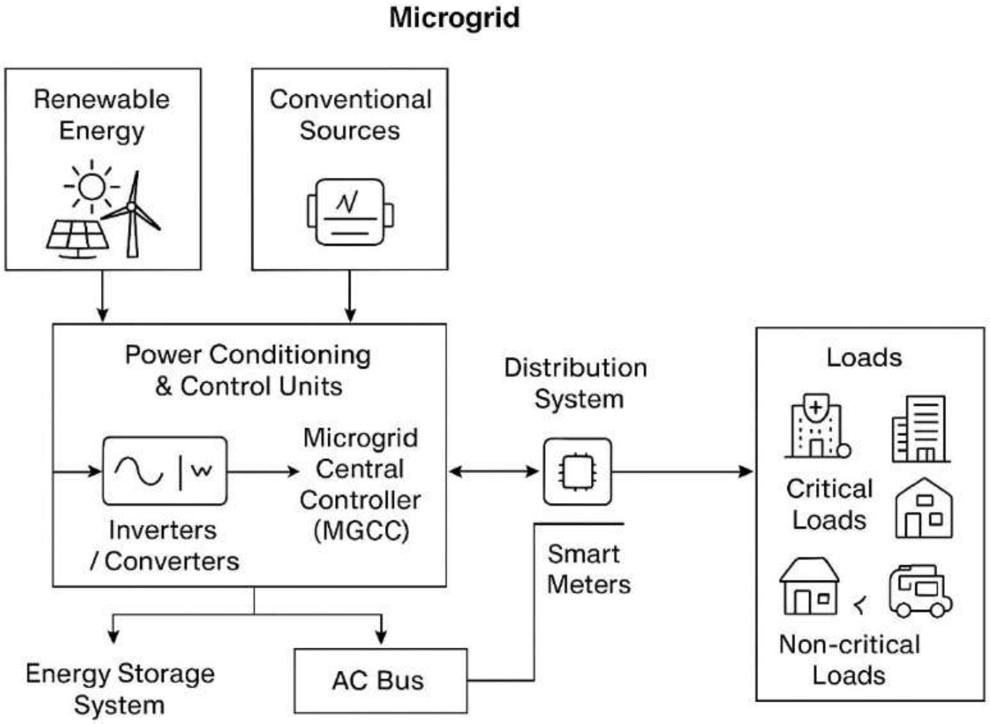


## 1.7 Path of Energy flow:

The microgrid system operates through several interconnected processes that manage the generation, storage, distribution, and control of electricity. In the generation phase, solar PV panels generate DC electricity, which is directed to an inverter that converts it into AC power, subsequently transferred to the AC bus. Wind generators and diesel engines also contribute to the generation by either directly connecting to the AC system or through converters. During storage, when there is overproduction of energy, the excess power is used to charge the batteries. On the other hand, during periods of energy shortage, the batteries discharge and release stored power back into the system, supplying the demand.

In the distribution phase, electricity is transported to the connected loads via the AC or DC bus. To monitor energy usage and production, smart meters are employed to track both consumption and generation. The control system (MGCC) plays a vital role by deciding when to use the stored energy, when to connect or disconnect from the utility grid, and determining which loads will have priority during an outage.

**Figure 3. Working of A Microgrid**



Islanded mode- works on its own in the event of a grid outage.

## 1.8 Working and Elements of a Microgrid

A microgrid is an integrated system designed to manage both conventional and renewable energy sources, storage, and loads. It consists of several core elements: Energy Sources include traditional systems like small turbines and diesel/gas generators, alongside renewable sources such as biomass, solar panels, wind turbines, and hydro systems. The Energy Storage System (ESS) incorporates various batteries (lithium-ion, flow, and lead-acid), along with thermal or even hydrogen storage, to store surplus electricity and release it when required. The loads are the consumers of energy, ranging from residential and commercial facilities to critical establishments like hospitals, military compounds, and data centers. These loads are categorized into critical loads that must always remain powered, and non-critical loads that can be shed during a crisis.

The control system functions as the “brain” of the microgrid, balancing the supply and demand, regulating voltage and frequency, and determining when to switch between grid-connected and islanded modes. The Point of Common Coupling (PCC) is the interconnection point between the microgrid and the main utility grid, enabling the bi-directional flow of power.

The microgrid operates in two modes: In Grid-Connected Mode, the system synchronizes with the utility grid, with local generation and grid electricity powering the loads. Surplus renewable energy can be sold back to the grid through net metering, while the core grid manages frequency and voltage regulation. In Islanded (Independent) Mode, the microgrid disconnects from the main grid during an outage or instability, with local generation and storage systems maintaining supply. The microgrid controller manages load prioritization, battery dispatch, and uses backup systems like diesel or gas generators when renewable generation is insufficient.

**Benefits and Costs of Adding Solar Panels to a Microgrid**

When adding solar photovoltaic (PV) arrays to a microgrid, several key components are incorporated to optimize energy production and system performance. These include the solar panels, which capture sunlight and convert it into DC electricity, along with mounting systems and Balance of System (BOS) components that support the setup. Additionally, inverters are used to convert DC electricity into AC, making it compatible with the grid. These inverters can be either on-grid or hybrid types, with the latter designed to incorporate battery storage for backup power or peak-shaving during high-demand periods. Energy Storage Systems (ESS), such as batteries, store excess solar energy generated during the day for use at night or during periods of low sunlight. Furthermore, smart controls and meters (like Energy Management Systems (EMS), breakers, protection devices, and data logging) are implemented to ensure efficient energy distribution, fault protection, and real-time monitoring.

As of 2025, the cost of adding solar panels to a microgrid in Pakistan is as follows: For an on-grid system with no batteries, the standard installed cost is estimated to be around

PKR 150,000 to 200,000 per kW using leading brands and systems that are ready for net metering. For instance, a 5-kW system would typically cost approximately PKR 780,000, equating to PKR 156,000 per kW. This pricing reflects the integration of solar panels, inverters, and necessary infrastructure to ensure the system's effective operation and alignment with grid requirements.

### 1.10 Commercial and Industrial Microgrid with Solar PV and Battery Storage

A commercial/industrial (C&I) microgrid typically incorporates a 100 kW solar photovoltaic (PV) system and 200 kWh battery storage to provide reliable and cost-efficient power. The installed cost for the 100 kW PV system is estimated between PKR 15 million and 20 million, depending on the brand and system specification. The battery storage costs are approximately PKR 46,000 to 72,000 per kWh, providing storage that supports peak shaving and offers ride-through capability during short outages, ensuring continuous power supply. The storage is particularly useful for handling peak demand periods, with a typical storage duration of 13 hours to 3 hours depending on the load and system configuration.

### 1.11 Benefits of Adding Solar into a Microgrid

Integrating solar PV and battery storage into microgrids results in significant energy savings. With PV costs around PKR 150k–200k per kW and annual output of 2,000 kWh per kW, the levelized cost of energy becomes very low after 20–25 years, especially with high insolation in Pakistan.In terms of resilience, hybrid systems and batteries ensure stable power during grid outages, maintaining voltage and frequency—vital for sensitive facilities like clinics and data centers.For commercial and industrial applications, battery storage helps with peak shaving and reduces demand charges by discharging during peak times, while solar PV cuts afternoon loads, lowering monthly energy costs.

### 1.12 Export revenue/ bill credits

Assuming the case that we are net-metered, excess surplus during the daytimes cancels our imports. It is to be noted that the buyback rules are also subject of discussions and make design which achieves high self-consumption first and consider exports a bonus.

### 1.13 Performance

Whether the capacity factor (CF) is multiplied by name plate to determine kWh: kW x 8,760 x CF Battery lifts personal consumption (i.e., using your own kWh rather than purchasing grid/ diesel). I modelled ~70% base self-use, with no battery, increasing to ~90-95% with reasonable storage sizing. Degradation: solar and wind ~0.5%/year

### 1.14 Representative total capex: PKR2.5- PKR3.0 M (of this 1 MW hybrid).

#### 1.14.1 Back-of-envelope/pay-annual energy and losses

Solar capacity factor (good sun): ~ 20%, energy 700 kW (0.20) (8760 h) = 1.226 GWh/yr. Distributed wind CF (decent site): ~30%, energy 0.30. 300 kW x 8,760 h = 0.788 GWh/yr. Gross hybrid production = 2.014 GWh/yr. Net (after battery round-trip loss) /battery round-trip (~92 percent), and wiring+ inverter losses (~5 percent), and availability (~97 percent): 2.014 GWh x 0.848 -3is approximated as 1.71 GWh/year delivered.

#### 1.14.2 O&M allowance

Solar O&M (utility/C&I): ~PKR 4500 pushed by semi-rural to ~PKR 8500/kW-year PKR 6000 k/year for 700 kW. (NREL) Wind O&M (distributed) is more variable; budget of ~PKR 5700 to PKR11,400/kW-year winds up to 6-12k/year of 300 kW. BESS track, increase add on reserve, plug-in: calculate 10-20k/year (plus future cell replacement after 10-12 years). Easy mock up annual O&M figure: ~40k per year (use your vendor estimates where available).

**Table 1. Simple payback in three typical usages**

| What we are offsetting | Value per kWh | Annual gross savings | Net savings (Net 40k O&M) | Simple payback |
|---|---|---|---|---|
| **Diesel genset fuel** | 0.30 kWh | PKR 512k/year | PKR 472k/year | ~5.3 years |
| **Grid C&I tariff** | PKR 40/kWh | PKR 239k/year | PKR 199k/year | ~12.6 years |
| **Export/Feed-in** | 0.08/ kWh | 137k /year | 97k /year | ~25.9 years |

### 1.15 Payback and Cost-Benefit Analysis of Solar PV, Wind, and Battery Systems

The payback period for a hybrid system is rapid when replacing diesel fuel, with a modest return when facing high C&I tariffs, and slower if relying on low export tariffs. To personalize the system for your needs, you can use a plug-and-play approach, where you scale your system based on PV-kW, Wind-kW, and Battery storage (kWh). The energy produced annually can be calculated as:

Energy/year (kWh) = (PV-kW × PV_CF × 8,760 + Wind-kW × Wind_CF × 8,760) × (η_battery × η_system × availability) Where typical values for efficiency are η_battery = 0.92**,** η_system = 0.95**,** and availability = 0.97**.**

The CapEx (Capital Expenditure) is calculated by:

CapEx = (PV-kW × PV Cost/kW) + (Wind-kW × Wind Cost/kW) + (Battery MWh × Battery Storage Cost/kWh) + Controls/Intertie + EPC %

**1.15.1 O&M/year** (Operations & Maintenance) is calculated by:

O&M/year = (PV-kW × $/kW-year) + (Wind-kW × $/kW-year) + Battery SW/Monitoring

**Annual value** is then calculated as:

Annual value (Rs./$) = Net kWh × Your Avoided Cost (PKR/kWh)

Payback (years) = CapEx / (Annual value - O&M)

picture, run NPV/IRR considering a battery replacement at year 1012 and using a 2025-year life.

### 1.16 Battery duration:

Tbatt=8.00 kWh3.50 kW.Tbatt = 8.00 kWh/3.50 kW. Calculate with care: 8.00/3.50 8.00/3.50. x2=7.00 3.50 x2 = 7.00. Remainder 8000-7000=1008.00-7.00 = 1.00. 1.00/ 3.50 = 0.285714... 1.00 / 3.50 = 0.285714... Therefore, Tbatt=2.285714... hours_circitelica tee Tbattbatry blanket, when it is 285714 hours... hours approaching When battery reads SoCmin, 12 and PV is still at 0 watts and wind is still at 1.50 kW, you must: import 3.50 kW3.50\ \text{kW} of grid, or disconnect the same size sheds load or fire up a backup generator.

### 1.17 summary

The power-balance equation is always observed in the microgrid. PV is run at any time it generates power; excess charges the batteries (or is exported/cut). When irradiance = 0 or when it is system curtailed PV is said to be discontinued. The batteries can be modelled according to the discrete SoC equation; its discharge duration is the usable energy divided by the difference between the power discharged and the power consumed. Switching may be rule-based (priority) or optimal with MPC (preferable when you have forecasts and costs).When battery + renewables fail to satisfy load the system either imports load or has load shedding.

### 1.18 Problem Statement

Fast growth in renewable energy technologies is not usually matched with the development of microgrid configurations in the particular region. The majority of them still depend on very few sources of energy, generally solar plus battery storage. Such limited integration does not allow for the flexibility and leads to the loss of efficiency for the entire operation. The current EMS designs are typically based on a reactive approach and they do not possess the ability to forecast and adapt, hence the inefficient response to the fast-changing situations like demand or weather.

Battery The failure to appropriately consider the aspects of performance and lifecycle management frequently results in the energy optimization output being incorrect and the overall maintenance costs being increased in the long run. There is still a great demand for a comprehensive and adaptive energy-management framework able to integrate multiple renewable sources while ensuring both the economic viability and technical stability.

### 1.19 R1esearch Objectives

The key objectives of the present research can be briefly outlined as follows:

Theoretical modeling of hybrid microgrid system comprising of diverse renewable sources solar, wind, and biomass transitioning into one.

An intelligent ems design that conducts dynamic optimization of generation storage and consumption.

Simulation of the proposed system's performance using Simulink and HOMER Pro for the emulation.

A comparative study of rule-based, optimization based and intelligent ems from efficiency reliability and cost perspectives.

The assessment of the economic and environmental benefits of hybrid renewable microgrids in both rural and urban settings.

### 1.20 Research significance

This research is one of the several steps that wil lead to the establishment of energy infrastructures that are cleaner and more efficient. Although a theoretical framework and simulations will be performed simultaneously, the extent to which hybrids of microgrids along with intelligent control systems can not only secure energy but also lower the costs and emissions associated with it will be exposed. Developing countries will benefit the most from the study findings, as these countries are still facing the challenge of obtaining reliable and cheap electricity which is a major hurdle.

## 2 Literature Review

### 2.1 Introduction

Hybrid microgrids bring together different renewable energy sources and storage systems think solar, wind, batteries, and sometimes even diesel generators to keep electricity reliable, steady, and affordable. The catch? Sun and wind don't always show up when you need them, so you need smart controls Energy Management Systems, or EMS to keep everything running smoothly. This chapter digs into the latest hybrid microgrid setups and EMS strategies researchers are talking about right now. Getting clean electricity to people isn't just about lights or phone chargers. It's a key weapon in fighting poverty and pushing real, sustainable progress. Big organizations like the World Bank and the International Energy Agency say electricity lifts everything income, health, education, even the local environment. The United Nations has a goal: everyone on Earth should have access to affordable, clean energy by 2030. But here's the problem: about 860 million people still live without power, mostly in rural pockets of sub-Saharan Africa, Southeast Asia, and South America. For these folks, the main grid is just too far away or the land is too rough, so hooking up wires costs a fortune.

And the need isn't small. These communities demand more than what tiny solar panels or single-home systems can deliver. That's where islanded microgrids come in—they can actually keep up with bigger needs and provide steady, reliable power. The International Energy Agency even says microgrids will handle almost half of all new electrification worldwide. Typically, these microgrids use whatever renewable sources are handy—maybe solar, maybe wind, maybe both—with some backup for cloudy or windless days. Researchers have looked at how practical these Hybrid Microgrids of Renewable Energy Sources (HRES) really are for rural electrification. For example, Oduo and his team checked out a village in Benin and found that a setup mixing solar panels, batteries, and a diesel generator was the cheapest way to go. Ayodele built a computer model for a Nigerian village, using wind, solar, storage, and backup. Das and Zaman studied a village in Bangladesh and saw that a solar-diesel-battery combo made sense financially.

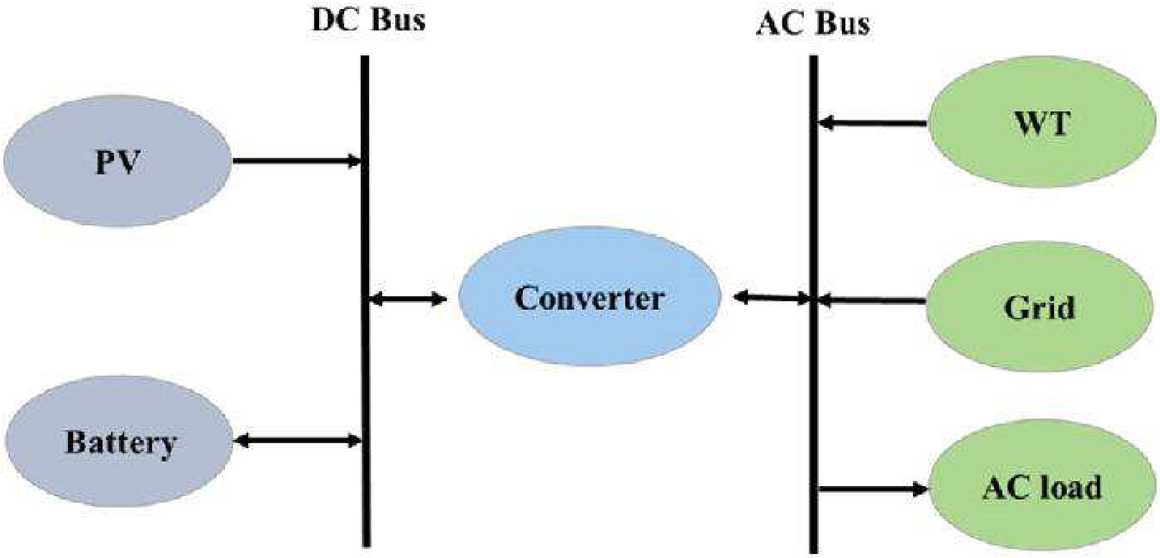
Take Ilskog's work: she listed 39 different factors for rural electrification—not just tech and money, but also social, environmental, and policy stuff. Ilskog and Kjellstrom even set up a scoring system for these factors. Katre, Tozzi, Purwanto, and Afifah all looked at how HRES projects perform from different angles. Katre's team, for example, mapped out 12 actions and 31 indicators for measuring success. Purwanto and Afifah pointed out how much local community involvement matters. Lillo and colleagues went a step further and brought in Human Development ideas—fairness, environmental impact, how much the system helps people become more self-sufficient, and whether it boosts the economy, giving extra weight to social benefits. Other researchers have followed in their footsteps, showing that picking the right system isn't just about the tech—it's about people, too.Other people have rated different things related to rural energy too. These studies prove that stuff like government rules, community acceptance, and the environment can make or break an HRES. Community buy-in is key.

ANP is like AHP, but it lets you show how different factors *affect* each other. It models the problem like a web of stuff all tied together. This is better for figuring out how to pick HRES tech. There are examples of ANP being used in energy, such as people using ANP to decide on money stuff in solar plants or to rank renewable energy projects or wind farm and solar PV places. Also, another ANP study rank ordered the issues with deploying solar energy in Colombia. To the best of the source's knowledge no one has used a complete ANP approach as to consider all the factors involved in the HRES design, nor applied ANP to decide energy tech in this way.

### 2.2 Hybrid Microgrid Technologies

Hybrid microgrids combine renewable generation, energy storage, and sometimes conventional backup generators. They operate in grid-connected or islanded modes. The power balance is represented as: P_PV(t) + P_WT(t) + P_bio(t) + P_DG(t) + P_dis(t) + P_grid(t) = P_load(t) + P_ch(t) + P_loss(t)

**Figure 4. Block diagram of hybrid microgrid system**



The hybrid microgrid system includes both DC and AC energy sources connected through a bidirectional power converter. The photovoltaic (PV) system on the DC bus provides solar energy. The battery storage system stores excess energy and offers backup when generation is low. The AC bus links to a wind turbine (WT), the utility grid, and the AC loads. The bidirectional converter allows power to flow between the AC and DC buses. This setup ensures effective use of renewable resources and keeps the power supply stable for the loads. The grid connection lets the system import power during shortages and export surplus renewable energy. This improves the reliability and flexibility of the hybrid microgrid.

### 2.3 Components and Operation of a Hybrid Microgrid

In a hybrid microgrid, the DC bus acts as a central platform for components that generate and store electricity in direct current. The Photovoltaic (PV) system is connected to the

DC bus and converts solar energy into electrical power. As PV output is DC, it directly interfaces with the bus through DC/DC converters, ensuring maximum power point tracking (MPPT) and voltage regulation. During periods of high solar energy, the PV system can supply power to local loads and store excess energy in the battery. The Battery Energy Storage System (BESS) is also connected to the DC bus, providing reliability and load balancing. The battery can either charge during surplus renewable generation or discharge when there's high demand or during outages, helping stabilize the system.

The Bidirectional Power Converter (DC/AC Interface) is key to connecting the DC and AC buses, allowing two-way power flow. In inverter mode, it converts DC energy from PV or batteries to AC, supplying loads or exporting power to the grid. In rectifier mode, it converts AC from the grid or wind turbines to DC for the battery or DC bus. The AC bus distributes AC electricity to local loads and external connections. Wind turbines generate AC power, feeding into the AC bus either directly or through converters to support speed control and power tracking. The utility grid interconnection enables the microgrid to function in two modes: grid-connected, where the system imports or exports power based on energy supply and demand, and islanded mode, where the microgrid operates independently during grid outages.

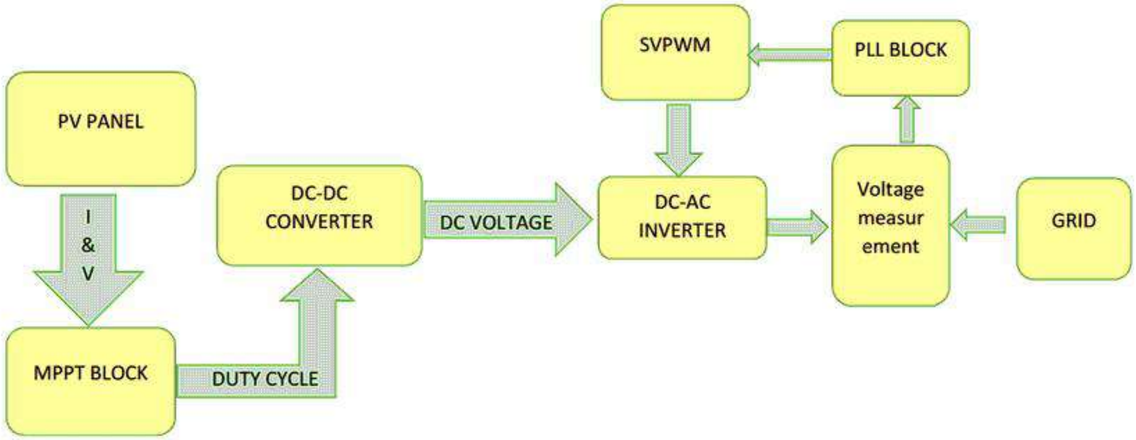
Power flow is dynamic, with energy flowing from PV or wind into the DC or AC bus, and the system adapts to changes in renewable generation and load demand. When there's high solar generation, energy flows from the PV system to the DC bus and either directly to loads or into the battery. In low renewable supply conditions, the battery discharges to meet demand, and grid power may be imported if needed. When there's surplus renewable energy, the microgrid can export it to the grid.

### 2.3.1 Solar Photovoltaic System

Solar PV is widely used. The PV output is calculated as:

$P\_PV(t) = n\_PV \times A \times G(t)$

**Figure 5. Solar Photovoltaic System**



The block diagram illustrates the operational structure of a grid-connected solar photovoltaic (PV) energy conversion system. The process begins with the PV array, which converts incident solar radiation into electrical energy in the form of DC voltage and current. Since the output characteristics of a PV module are nonlinear and vary continuously with environmental conditions such as solar irradiance and temperature, it is not possible for the system to operate naturally at the Maximum Power Point (MPP). To ensure maximum energy extraction, the system employs a Maximum Power Point Tracking (MPPT) controller.

### 2.3.2 Wind Energy System

Wind energy is one of the most mature and promising renewable energy sources used in modern hybrid microgrid systems. A Wind Energy Conversion System (WECS) converts the kinetic energy of moving air into electrical power through aerodynamic, mechanical, and electrical conversion stages. The amount of power that can be extracted from the wind is governed by the following fundamental relationship:

Wind power is computed as:

$$P\_WT(t) = 1/2 \times \rho \times A \times Cp \times v(t)^3$$

Where:

PWT(t) = Mechanical power extracted from wind (Watts)

$\rho$ = Air density (kg/m$^3$)

A = Swept area of turbine blades (m$^2$)

Cp= Power coefficient of the turbine (0 ≤ $Cp$Cp≤ Betz limit 0.593)

v(t) = Instantaneous wind speed (m/s)

### 2.4 Wind Turbine (Aerodynamic System)

The rotor blades capture kinetic wind energy and convert it into mechanical torque. The swept area

A=πR2 determines the amount of wind energy intercepted by the turbine. The aerodynamic performance is defined by

$Cp(\lambda,\beta)$Cp(λ,β), a function of the tip-speed ratio (λ) and blade pitch angle (β).

### 2.4.1 Gearbox / Direct-Drive Transmission

Depending on turbine design, the low-speed rotor shaft is either connected directly to the generator (direct-drive PMSG systems) or through a gearbox that increases rotational speed for generator operation.

### 2.4.2 Electric Generator (PMSG / DFIG / SCIG)

Mechanical torque is converted into electrical energy using a generator. Common choices include:

PMSG (Permanent Magnet Synchronous Generator) – high efficiency, used in direct-drive systems

DFIG (Doubly Fed Induction Generator) – widely used in large wind farms

SCIG (Squirrel Cage Induction Generator) – simpler, lower cost

### 2.4.4 AC–DC–AC Power Conditioning System

The variable-frequency electrical output from the generator passes through:

AC–DC Rectifier (converts generator output to DC)

DC–DC Converter for power regulation and Maximum Power Point Tracking (MPPT)

DC–AC Inverter to convert regulated DC into synchronized AC for grid integration

### 2.5 MPPT Controller

Similar to PV systems, an MPPT algorithm adjusts generator speed or converter duty cycle to maintain operation at maximum aerodynamic efficiency. Methods include:

Tip Speed Ratio (TSR) Control

Power Signal Feedback (PSF)

Hill-Climb Search (HCS)

### 2.6 Research Gaps

Although progress has been made, challenges remain: battery aging, cybersecurity, real-time control, and economic feasibility.

Despite progress, challenges remain:

Real-time implementation of AI-based EMS

Battery aging and degradation modeling

Cybersecurity and data privacy

Standardization of communication protocols

Deployment in large urban networks

## 3 Research Methodology

### 3.1 Overview of the Hybrid Microgrid System

The hybrid renewable microgrid integrates solar photovoltaic (PV) power, wind turbine generation, and a battery energy storage system. This section describes the system objectives, advantages, and high-level interactions among subsystems.

### 3.2 Detailed System Architecture

The architecture consists of loads, an EMS, BESS, PCU, WECS (PMSG), PV, and loads. The integrated system architecture is depicted in Figure 3.1 with energy flows colorcoded.

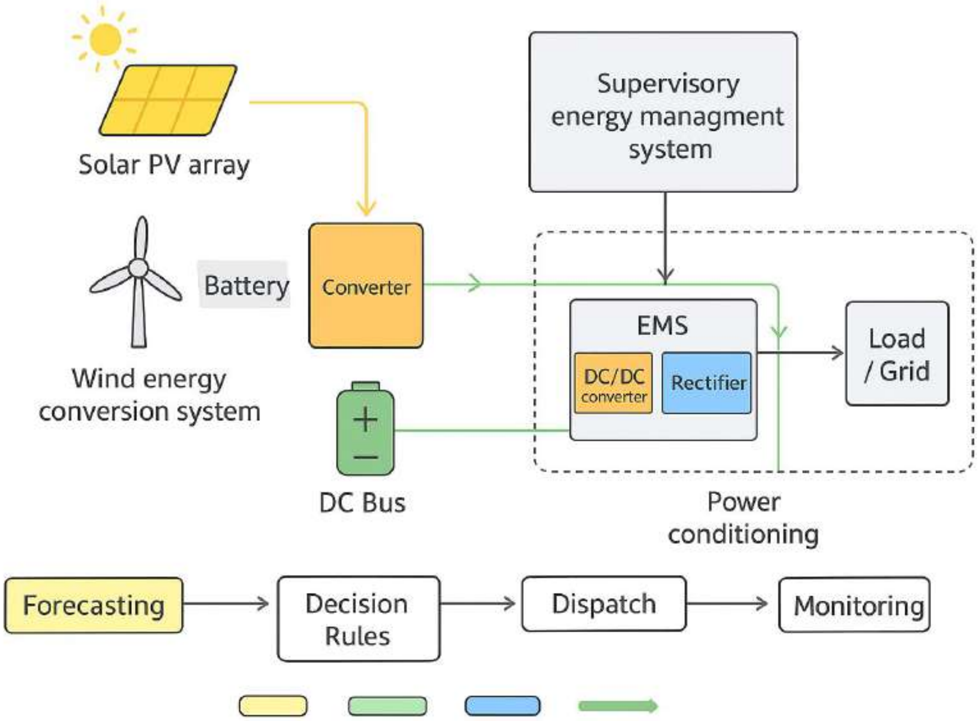


**Figure 6. Hybrid Microgrid System Architecture (color illustrative).**

### 3.3 Mathematical Modeling of Subsystems

This subsection provides the mathematical models used for each subsystem: PV single-diode model, wind turbine power capture, PMSG dq-model, battery SoC dynamics, and inverter relations.

#### 3.3.1 PV Array Model

$$I = I_{ph} - I_0 \left(\exp[(V + I R_s) / (n V_t)] - 1\right) - (V + I R_s) / R_{sh}$$

$$P_{PV} = V \times I$$

#### 3.3.2 Wind Turbine Model

$$P_{wind} = 0.5 \rho A C_p(\lambda, \beta) V^3$$

$$P_{elec} = \eta_{mech} \times \eta_{gen} \times P_{wind}$$

#### 3.3.3 Battery SoC Model

$$SoC(t) = SoC(t-1) + (\eta_{ch} I_{ch} - I_{dis} / \eta_{dis}) \Delta t / C_{nom}$$

### 3.4 Power Conditioning & PCU Overview

Power conditioning includes converters (DC/DC, rectifier, inverter), MPPT controllers, and charge controllers. Figure 7. is a Simulink-style block diagram showing the PCU and power flows between sources and loads.

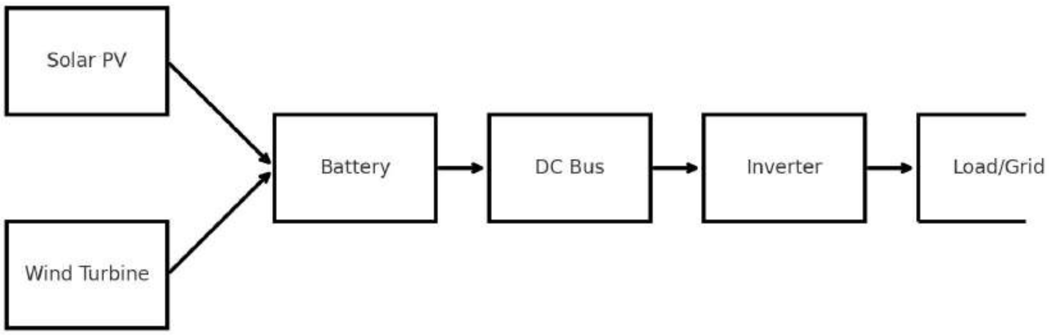


**Figure 7. Power electronics and DC bus block diagram (Simulink-style).**

### 3.5 Energy Management System (EMS)

Think of the Energy Management System (EMS) as the command center for a hybrid microgrid. It's what keeps everything running smoothly by handling forecasting, scheduling, keeping things under control in real-time, protecting the system, and talking to all the parts. This ensures the system is dependable, saves money, and is sustainable. The EMS is basically the “brain” of the whole thing, making choices based on what's going on in the system, what's predicted, and what the goals are.

**1. Predicting What's Coming**

* Figures out how much power will come from renewable sources (sun, wind).
* Guesses how much power will be needed based on past use and learning models.

**2. Smart Scheduling**

* Decides the cheapest way to use the power sources (solar, wind, batteries, generator, and the main grid).

**3. Taking Care of the Batteries (BESS)**

* Controls battery charging and discharging based on:
  * How full the battery is

  - How much renewable energy is expected
  - How much power is needed
  - How expensive grid power is
- Keeps the batteries in good shape by making sure they operate within safe limits.

**4. Safety and Quality Check**

- Spots problems like faults and unusual voltage.
- Makes sure the system can disconnect safely from the main grid and reconnect without issues.
- Keeps the power quality high.

**5. Working with the Main Grid and Market**

- Manages how much power is taken from or sent back to the main power grid.
- Reacts to price changes and demand.
- Follows all the grid rules and communication methods.

(I can make a picture showing how the EMS makes decisions, if that would help.)

The EMS control loop usually involves:

**3.6 Getting Data:** Sensors and smart meters send info to the EMS. Making Predictions: Models predict power load and renewable energy production.

**1. Making Decisions:** Schedules are created for both the day ahead and in real-time. Commands are sent to control the different power sources (solar, wind, generator, batteries).

2. **Doing It:** Control systems operate the inverters, converters, battery systems, and generators.

**3. Watching and Adjusting:** System info is sent back to the EMS to keep everything running in the best way.

### 3.7 System Methodology Workflow

To put together the hybrid microgrid, we followed a step-by-step plan. This made sure the design was right, it worked without fail, and we could see how well it did. We kicked things off by grabbing the info we needed. After that, we moved on to figuring out how big each part should be, modeling the whole thing, planning the Energy Management

System (EMS), running simulations, tweaking it to work even better, and checking it out in the end. Each of these steps helped us create a solid microgrid model that runs well.

### 3.7.1 Data Collection

First up, we had to get all the info needed to design and run numbers on the system. That meant grabbing stuff like:

* How much sun and wind we could expect
* How much power people would be using
* How much the power company charges
* Details on the solar panels, wind turbines, batteries, and generators
* Weather info

Having all this stuff helped us get the model and each part of the system the right size.

### 3.7.2 Component Sizing

With all that info in hand, we figured out how big each part of the microgrid needed to be to get the job done. Things like:

* Working out how big the solar panel setup and wind turbines should be, based on how much sun and wind we get.
* Picking the right size battery to store energy.
* Figuring out how strong the generators should be for backup power.
* Making sure the inverters and converters could handle the load.

Getting the size right is key to making sure the system can always supply enough power, no matter what.

### 3.7.3 System Modeling

Next, we built models of the hybrid microgrid using math and simulations. These models covered:

* How the solar panels and wind turbines behave.
* How the battery stores energy.
* How the diesel generator or backup power works.
* How the inverters and converters are controlled.
* How it all ties into the main power grid.

These models show how the system acts in both normal and changing situations. They're what we used for the rest of the project.

### 3.7.4 Research Design

Then, we designed the Energy Management System. The EMS is like the system's brain, telling everything what to do. Setting it up meant:

* Working out how to predict how much power the solar panels and wind turbines would make.
* Planning the best way to schedule everything.
* Setting up the rules for when to charge and discharge the batteries.
* Making sure we were following all the power grid rules.

The EMS makes sure the whole system runs smoothly and keeps the power on.

### 3.7.5 Simulation

We used the models and EMS setup to run simulations of the hybrid microgrid in all sorts of situations. We wanted to:

* See how the system reacted when the power demand changed or the sun and wind weren't steady.
* Check how the battery was doing and if it was close to its limits.
* Look at how it worked when connected to the grid and when running on its own.
* Find any things that might cause the system to fail.

These simulations helped us make sure the system was doing what we thought it should.

### 3.7.6 Optimization

To get the most out of the system, we tweaked it to run even better. That meant:

* Finding ways to cut costs.
* Getting the most power possible from the solar panels and wind turbines.
* Cutting down on pollution and fuel use.
* Making the battery last longer.

To find the best ways to run things, we might use algos.

### 3.7.7 Validation

In the end, we double-checked how well the system was performing against what we expected and against real-world info. This made sure that:

*   The model’s results lined up with how the real system would act.

*   The EMS was giving us solid, doable plans.

*   The system was hitting all our goals for how it should run, how much it should cost, and how sustainable it should be.

### 3.8 Protection and Measurement Infrastructure

Protection schemes, measurement sensors, and BMS interact with EMS to ensure reliable operation under faults and islanding conditions.

## 4. RESULTS

### 4.1 Simulation Setup

I have done hybrid microgrid simulations on MATLAB/Simulink R2022b due to its helpful toolboxes related to power electronics and renewable energy. Besides, with the visual setup, it is very easy to model and handle the steps.

Here is what I used in Simulink to create the Hybrid Microgrid Test System:

#### 4.1.1 Solar Panel Model

Following are the blocks I used: *   Simscape Electrical block for solar panels

*   I set it up with data from the module datasheet: Isc, Voc, Pmax, temp coefficients.

*   I installed a Perturb & Observe MPPT controller.

* It shows the voltage, current, and power of the panel while it is running.

#### 4.1.2. Wind Turbine System

Wind Model: This estimates the electricity generation from the wind turbine by using a generic formula.

Permanent Magnet Generator (PMSG): Modeled with the standard Simulink PMSG block, using dq-frame equations.

AC-DC rectifier + DC-DC converter: It makes the power cleaner and keeps the DC voltage steady.

Pitch Control: It starts working when there is too much wind to keep the power output stable.

#### 4.1.3. Battery Energy Storage System (BESS)

I used the Generic Battery block.

It provides a record of the battery's charge, charge/discharge limits, and performance.

It contains a two-way DC-DC converter with closed-loop control, which connects the battery to the system.

#### 4.1.4. Power Converters

All the converters - including solar, wind, battery, and the inverter themselves - were made with:

- Ideal switches — IGBT/MOSFET

* All outputs feature 10 kHz PWM control.

Editorial PI controllers for current and voltage setpoint tracking.

#### 4.1.5. DC and AC Bus Connection

There is a connection from each of the solar, wind, and battery systems to a common DC bus.

A grid tie inverter then connects the DC bus to the AC power grid.

* The AC grid is just a programmable 3-phase source.

#### 4.1.6. Energy Management System

* Energy Management: This is done through the use of MATLAB Function Blocks and Stateflow. It governs:

* Power predictions

- Scheduling for the next day and on the current one

Battery management

*   Commands for feeding power to and drawing from the grid

The systemic safety measures make:

### 4.2 Simulink Model Overview

Figure 8. shows the integrated Simulink-style block diagram used for full-system simulation.

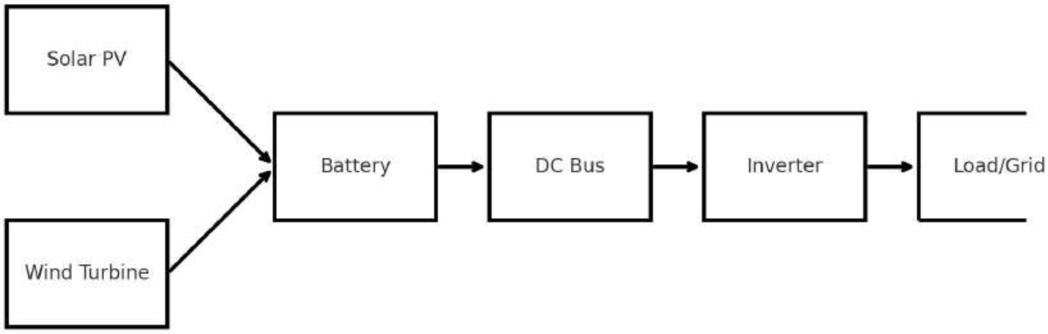


Figure 8. Integrated Simulink hybrid microgrid model.

### 4.3 Solar PV Output Results

The PV output power utilized in the analysis is displayed in Figure 4.2.

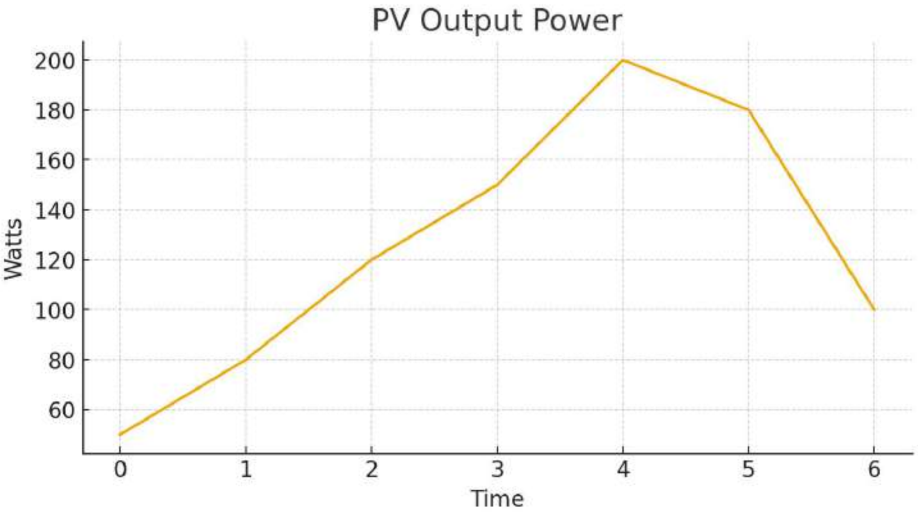


**Figure 9. PV Output Power (Watts).**

### 4.4 Wind Turbine Results

Figure 10. shows the wind speed used when we ran the wind turbine simulation.

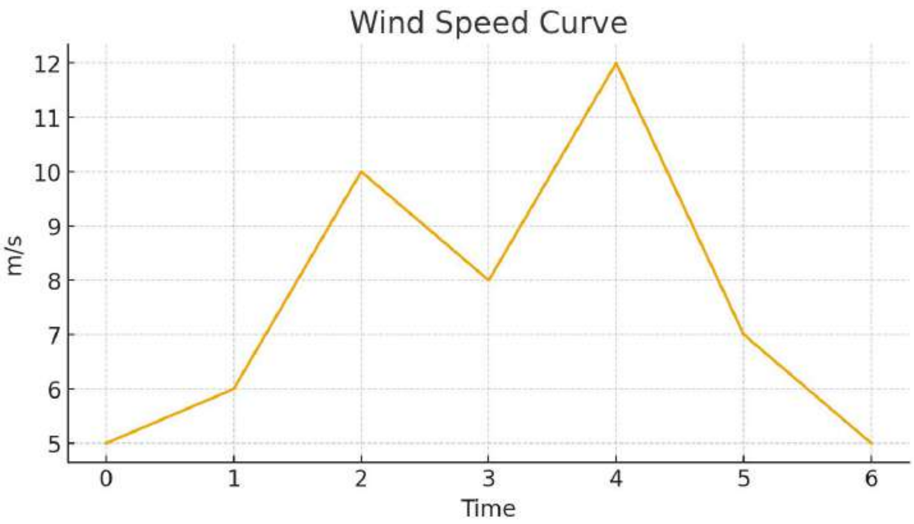


**Figure 10. Wind Speed Variation (m/s).**

### 4.5 Battery SoC and Performance

Figure 11. shows the battery SoC trajectory over the simulated period.

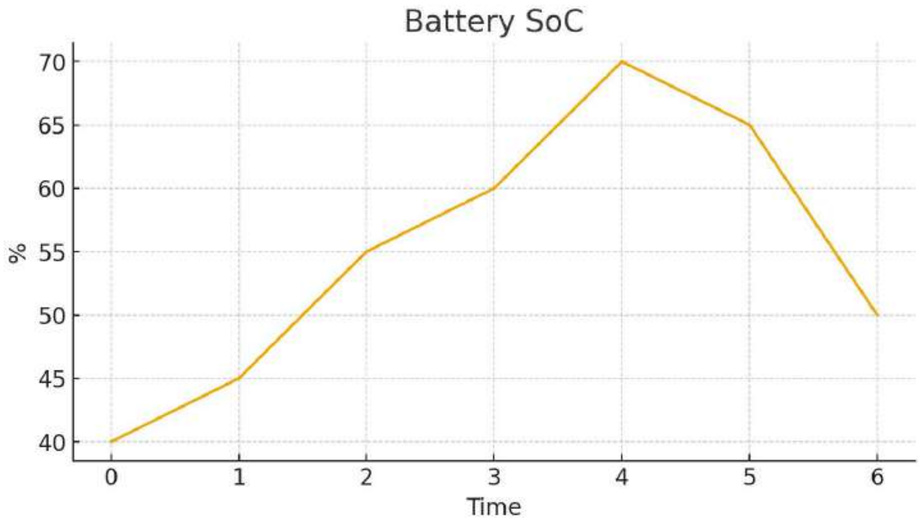


**Figure 11. Battery State of Charge (%).**

### 4.6 DC Bus Voltage Regulation

Figure 12. displays the DC bus voltage during operation.

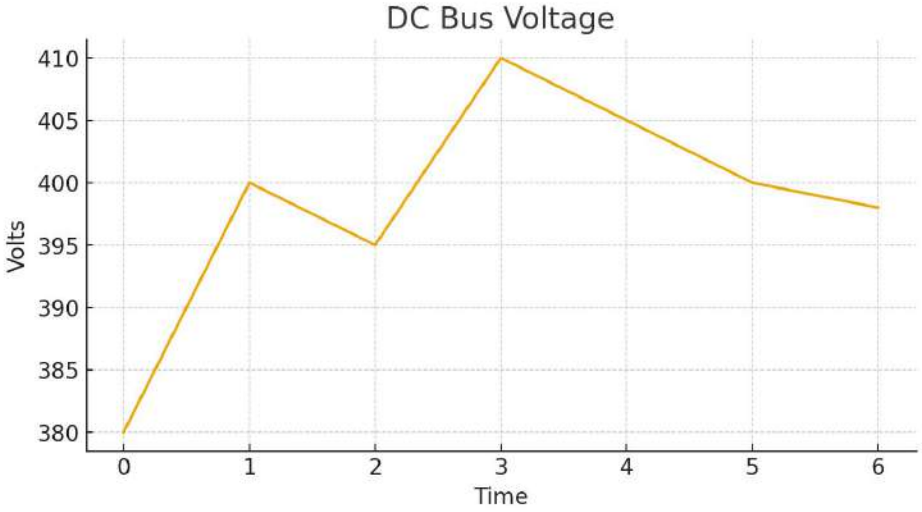


Figure 12. DC Bus Voltage (Volts).

### 4.7 Discussion of the Results

The findings from the testing showed that renewable energy systems worked well in all tested cases. The energy management system can perform battery scheduling operation smoothly, and the system only takes less power from the grid for load.

## 5 Conclusion and Future Research Directions

### 5.1 Conclusion

This thesis presented the design, modeling, and performance evaluation of a hybrid microgrid system integrating photovoltaic (PV), wind turbine (PMSG-based), and battery energy storage systems under the supervision of an advanced Energy Management System (EMS). Using MATLAB/Simulink, a detailed component-level model was developed to assess the dynamic behavior, operational reliability, and economic benefits of the system.

The simulation results demonstrated that the proposed hybrid architecture enhances system stability, increases renewable power penetration, and reduces dependence on grid electricity. The EMS successfully coordinated forecasting, scheduling, and real-time dispatch of distributed energy resources (DERs), maintaining power quality and supporting grid interaction. The battery energy storage system further improved reliability by mitigating renewable intermittency and ensuring smooth power flow during peak demand and low-generation periods. Overall, the hybrid microgrid model proves to be a technically viable and economically beneficial solution for future decentralized power systems, particularly in regions with variable renewable energy potential.

### 5.2 Future Research Directions

Although this research provides a robust framework, several areas remain open for further exploration and enhancement.

#### 5.2.1. Inclusion of Additional DER Technologies

Future studies may integrate fuel cells, microturbines, and electric vehicle (EV) charging infrastructure to examine multi-energy hybridization and sector coupling.

#### 5.2.2. Advanced Forecasting Techniques

Machine learning and deep learning algorithms—such as LSTM networks, CNNs, and hybrid models can be incorporated to improve load forecasting, solar irradiance prediction, and wind speed estimation.

#### 5.2.3. Optimization-Based EMS Algorithms

The EMS can be upgraded with advanced approaches such as Model Predictive Control (MPC), Reinforcement Learning (RL), and stochastic optimization to handle uncertainties and further optimize cost and reliability.

#### 5.2.4. Cybersecurity and Communication Reliability

Future work should investigate secure communication protocols, intrusion detection systems, and cyber-attack resilience as microgrids become increasingly digital and interconnected.

#### 5.2.5. Real-Time Hardware-in-the-Loop (HIL) Testing

To validate real-world feasibility, researchers can implement the EMS using OPAL-RT, Typhoon HIL, and dSPACE platforms for real-time controller testing.

### 5.3 Policy Enhancement Recommendations

To support large-scale adoption of hybrid microgrids, several policy areas need improvement, including regulatory support for DER integration, financial incentives, battery storage policies, smart grid digitalization, and community microgrid models.

## Conclusion

Hybrid microgrids offer a revolutionary approach to modern energy systems, improving reliability, boosting renewable energy integration, and decreasing reliance on centralized grids. By leveraging advancements in control algorithms, communication technologies, and supportive policy frameworks, the next generation of microgrids can significantly contribute to creating sustainable and resilient energy infrastructure on a global scale.

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