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Design and Development of Hybrid Renewable Energy System with Energy Storage

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Abstract: *The rising world energy demand, combined with the necessity of curbing carbon emissions, has expedited the advancement of hybrid renewable energy systems (HRES) that have several energy sources. This article gives the design and development of a hybrid renewable energy system with solar, wind, and hydro power and an energy storage system to provide a constant and reliable power supply. By taking advantage of the complementary characteristics of these renewable resources, the system will maximize energy reliability, efficiency, and sustainability.*
The system to be proposed will maximize power generation by utilizing a smart energy management approach that dynamically adjusts the contribution of each source in accordance with real-time environmental conditions and load demands. Solar photovoltaic (PV) panels produce electricity during the day, while wind turbines generate power when it is windy to supplement solar power generation. Hydro power is also a steady source of energy, especially for areas with available water resources, to ensure reliable power generation even when solar and wind resources are low.
Simulation and experimental studies are performed to analyze the performance of the suggested hybrid system under different operating conditions. Findings show that the hybrid renewable energy system with energy storage effectively enhances power stability and lessens dependency on traditional grid-based electricity. The results point to its prospects for use in remote and off-grid areas, rural electrification, and sustainable energy programs.
This study contributes to the development of hybrid renewable energy technologies by introducing an optimized method for combining multiple renewable sources with energy storage. Through the use of such a system, it is feasible to attain a more robust, efficient, and sustainable energy solution, facilitating the global shift toward renewable energy and carbon neutrality.

Keywords: Hybrid Renewable Energy System (HRES), Solar Energy, Wind Energy, Hydro Power, Energy Storage, Smart Energy Management, Power Optimization, Grid Independence, Sustainable Energy, Renewable Energy Integration

I. INTRODUCTION

The accelerated depletion of fossil fuels and the increased environmental implications associated with greenhouse gas emissions have put renewable energy into greater global limelight as a clean and sustainable source. The innate intermittence and volatility of isolated renewable sources of power, e.g., solar and wind, restrict their ability to generate reliable and continuous supply of power. In order to overcome these issues, Hybrid Renewable Energy Systems (HRES) that use two or more renewable sources coupled with effective energy storage systems (ESS) have come forward as an effective solution for both grid-connected and off-grid systems.
A Hybrid Renewable Energy System (HRES) is a system that combines two or more renewable sources to utilize each other's strength and weakness and provide a constant and stable source of energy. By context, the amalgamation of photovoltaic solar (PV), wind power, and small-hydroelectric networks holds high degrees of potential towards diversified and power supplies. Solar energy, in readiness during daytime periods, tends to complement wind energy, which would be at maximum during nights and stormy sessions. Hydropower, by contrast, remains a constant source of

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base loads, particularly if available from permanent water sources within the region and is therefore pivotal as part of a strong hybrid system.

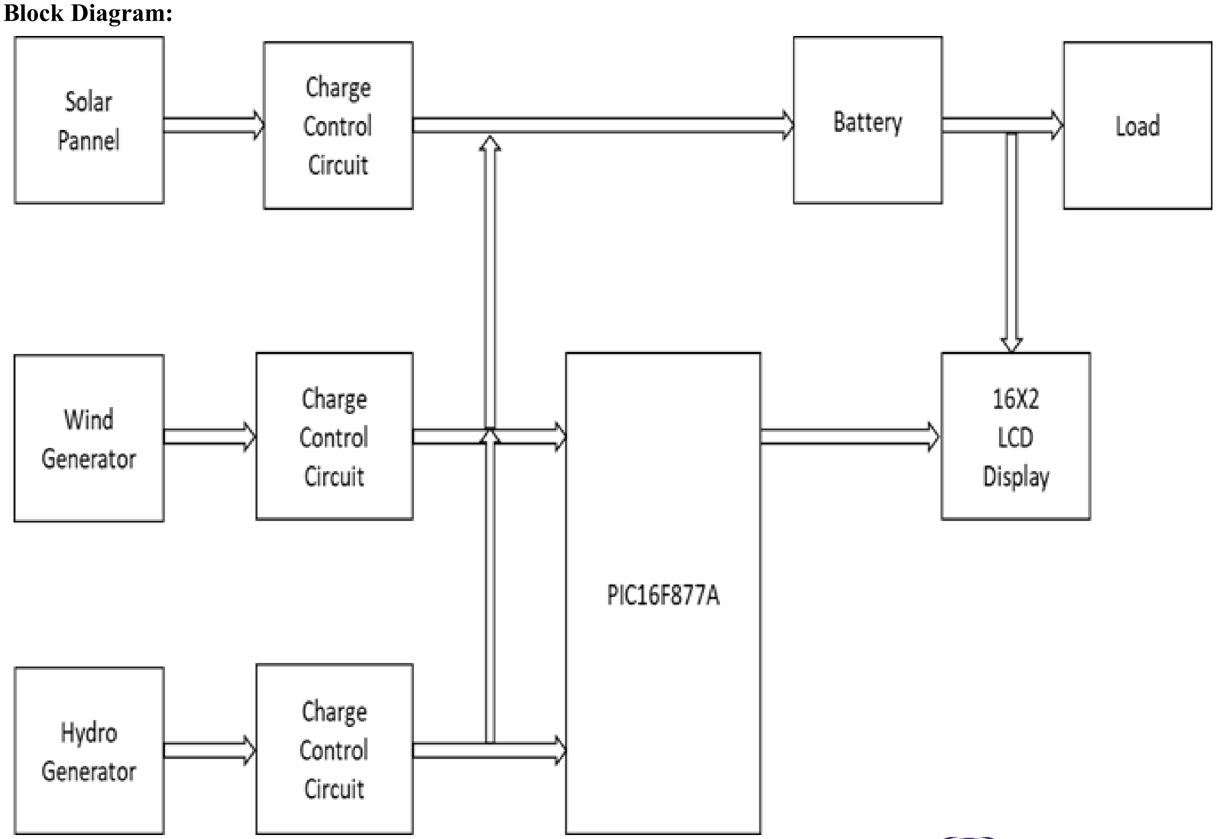
But the intermittent source nature of solar and wind power generation requires that advanced energy storage technologies, including battery banks, pumped hydro storage, or supercapacitors, be introduced to optimize supply and demand matching. The storage systems are important in saving excess power generated during high generation times and delivering it during low-generation times or peak demand times, thereby maximizing system reliability and flexibility.The development and design of a hybrid renewable energy system with built-in energy storage include a number of key considerations, such as resource assessment, system sizing, component selection, optimization of energy flow, control strategies, and cost analysis. By utilizing smart controllers and optimization software, the system can dynamically optimize the contribution of each source of energy based on real-time availability and demand to maximize efficiency and minimize wastage.

II. OBJECTIVES

1.Energy Reliability & Stability
2.Maximization of Renewable Energy Utilization
3.Minimization of Carbon Footprint
4.Enhanced Energy Efficiency
5.Energy Independence & Rural Electrification
6.Grid Stability & Resilience
7.Scalability & FlexibiliTY

III. BLOCK DIAGRAM AND WORKING

Block Diagram:



Block Diagram Hybrid Renewable Energy System

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Working:

The system is designed to harness energy from three types of renewable resources: solar, wind, and hydro. These sources are integrated into a unified system to efficiently generate and manage electrical energy. Each source has specific ratings and is connected to an individual control circuit to regulate the generated power before storing it in a battery and monitoring it through a microcontroller.

1.Renewable Energy Sources:

The system employs the following three renewable sources:

Solar Panel:

Rating: 10 Watts, 12 Volts

Function: Converts sunlight into electrical energy using photovoltaic cells.

Usage: Supplies a constant power output during daylight hours.

Wind Generator:

Rating: 5 Watts, 12 Volts, 300 rpm

Function: Converts wind energy into electrical energy using a small wind turbine.

Usage: Generates power whenever wind is available, including at night.

Hydro Turbine:

Rating: 5 Watts, 12 Volts, 300 rpm (same as the wind generator)

Function: Converts the kinetic energy of flowing water into electrical energy.

Usage: Provides continuous power if a steady water flow is maintained.

Each of these sources is connected to a dedicated control circuit that regulates and stabilizes its output before supplying it to a shared battery and control system. All three control circuits are designed identically for simplicity and ease of maintenance.

2.Control Circuit:

Each renewable energy source is connected to its own control circuit, which performs critical roles in power regulation and protection. The system contains three independent control circuits one for each source (solar, wind, and hydro).

components of control circuit are as follows:

IN4007 Diodes:

Purpose: Allow current to flow in only one direction, preventing stored energy from the battery from flowing back into the sources and potentially damaging them.

Function: Act as blocking diodes to prevent reverse current flow.

Indicator (LED or Status Indicator):

Purpose: Show the active status of each source, indicating whether it is generating and supplying power.

Function: Provide visual feedback for easy monitoring.

1000µF Capacitor:

Purpose: Filter and smooth the voltage output from each source.

Function: Eliminate voltage ripples and fluctuations to ensure a stable DC output suitable for battery charging and microcontroller

Input uses: Provides continuous power if a steady water flow is maintained.

Output Connections:

The regulated and filtered outputs of each control circuit are connected in parallel to:

The battery (for energy storage).

The microcontroller (for real-time monitoring).

3.Microcontroller Unit (PIC16F877A):

A PIC16F877A microcontroller is used to monitor and control the system, enabling automated and intelligent operation.

Functions of the Microcontroller:

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Voltage Monitoring:
The outputs from the wind and hydro control circuits are connected to the analog input ports (AN0 and AN1) of the microcontroller.
The microcontroller reads these voltages to monitor the power generation status of the wind and hydro sources.
Note: The solar source can also be monitored similarly in future expansions.
Voltage Display:
Purpose: Show the active status of each source, indicating whether it is generating and supplying power.
The monitored voltages are displayed on a 16x2 LCD, providing real-time updates on power generation.
The LCD is connected to the microcontroller's digital output pins (35 to 40).
Additional Components:
Crystal Oscillator (22 MHz):
Purpose: Provide a stable clock signal for the microcontroller's operation.
Connection: Pins 13 (OSC1) and 14 (OSC2) of the PIC16F877A.
Note: The oscillator circuit also includes 22µF capacitors to ensure stable operation and reduce noise.
This setup allows the microcontroller to operate precisely and efficiently process analog data from the renewable Sources.

4.Output to Battery and System Supply: The outputs from the solar, wind, and hydro control circuits are combinedin paralleland directly connected to a rechargeable battery.
Purpose of Battery Storage:
Energy Storage: Store the energy generated from all sources for later use.
System Supply: Provide continuous power to connected loads and system components
Display and Load Supply
The battery also powers a display system required to monitor the system performance and status.
Since essential components like the microcontroller and LCD require continuous power, the battery ensures the system remains self-sustaining and operational at all times, even when no energy is being generated (e.g., at night or during calm weather conditions). The out from the battery is also given to load and load is also the output directly from source

IV. PAY BACK PERIOD CALCULATION OF HYBRID RENEWABLE ENERGY SYSTEM

1.By assuming system ratting are as follows:
Solar: 800W
Wind: 400W
Hydro: 500W

2.Calculation of Daily Energy Output
Solar Power Output:
Number of solar panels = 2
Power rating per panel = 400W
Total solar power = Number of solar panels X Power rating per panel
= 800W
Average sunlight hours per day = 6h
Daily solar energy output =800W X 6h = 4.8 kWh
Wind Power Output:
Number of wind turbines = 1
Power rating per turbine = 400W
Total wind power = Number of wind turbines X Power rating per turbine
= 400W
Average wind hours per day = 5h
Daily wind energy output =400W X 5h = 2.0 kWh

Hydro Power Output:
Number of hydro generators = 1
Power rating per generator = 500W
Total hydro power = Number of hydro generators X Power rating per generator
= 500W
Average water flow hours per day = 10h
Daily hydro energy output = 5.0 kWh
So,
Total Daily Energy Generation = 11.8 kWh/day

3.Annual Energy Output Calculation
Total daily energy = 11.8 kWh/day
Number of days in a year = 365
Annual energy output = Total daily energy X Number of days in a year
= 4,307 kWh/year

4.Cost Calculation

Component	**Unit X Cost (₹)**	**Quantity**	**Total Cost (₹)**
Solar Panel (400W)	₹34,000	2	₹68,000
Wind Turbine (400W)	₹50,000	1	₹50,000
Hydro Generator (500W)	₹50,000	1	₹50,000
Battery (250Ah)	₹40,000	1	₹40,000
Charge Controller	₹15,000	1	₹15,000
Inverter (1.5kW)	₹22,000	1	₹22,000
Miscellaneous Costs (Wiring, Mounts, Civil work etc.)	₹30,000	-	₹30,000
Total System Cost	-	-	₹2,75,000

Table: Cost calculation of Hybrid Renewable energy system at big scale

5.Payback Period Calculation
Annual Savings from Energy Generation:
Electricity cost per kWh = ₹10
Annual energy output = 4,307 kWh
Annual Saving = Electricity cost per kWh X Annual energy output
Annual savings = ₹43,070 per year
Payback Period Calculation:
Payback period = Total system cost ÷ Annual savings
= ₹2,75,000 ÷ ₹43,070
= ≈ 5 years
If well maintained, this system can provide reliable power for 25+ years, with battery replacements every 5-7 years and minor maintenance.

V. ADVANTAGES,LIMITATIONS &APPLICATIONS

Advantages:

1. Continuous Power Supply

One of the biggest challenges of renewable energy is its intermittency. A hybrid system ensures round-the-clock energy availability by balancing different sources.

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Example: If solar energy is unavailable at night, wind or hydro can take over, ensuring uninterrupted electricity supply.

2. Higher Efficiency

Single-source renewable systems tend to waste excess energy during low-demand periods. A hybrid system has the ability to redirect excess energy to another source or store it effectively. Integration with smart grids and controllers maximizes energy utilization, making the system more efficient.

3. Lower Energy Storage Requirement

As several sources are combined, the dependence on costly battery storage systems is reduced. While a single solar system needs big batteries to save excess power for nighttime consumption, a hybrid system can switch to wind or hydro when the sun goes down.

This greatly lowers storage costs and prolongs battery life if batteries are employed.

4. Reduced Greenhouse Gas Emissions

Totally renewable energy sources equate to no fuel burning and drastically reduced carbon emissions. Less air pollution and less environmental harm from fossil fuels.

Assists in meeting climate objectives and aiding a sustainable energy future.

5. Long-term Cost Savings

Although the initial cost of infrastructure investment is high, long-term fuel savings, maintenance, and grid dependency costs make it financially worthwhile.

Hybrid systems also cut peak electricity bills and generate free energy after installation.

Limitation:

1. Technical Limitations

Intermittency and Variability: Solar and wind power output varies depending on weather, and thus power generation is uncertain.

Complex System Integration: Control of multiple energy supplies and energy storage devices involves sophisticated control systems and real-time monitoring.

Grid Compatibility Issues: The current electrical grids might not be compatible with the unpredictability of renewable energy, necessitating further infrastructure improvements.

2. Financial and Economic Constraints

High Upfront Cost: The installation cost of solar panels, wind turbines, hydro turbines, energy storage systems, and control equipment is high.

Operation and Maintenance Expenses: Some parts of the system require more maintenance compared to others, resulting in higher operational costs in the long run.

Energy Storage Expenses: Batteries and other forms of storage are costly and subject to wear and tear, affecting long-term economic viability.

3. Environmental and Geographical Challenges

Land and Space Requirements: Huge land or water sources are needed for large-scale hybrid systems, and these may not be available in all places.

Ecosystem Impact: Local aquatic ecosystems are interrupted by hydropower plants, and bird species may be under threat from wind turbines.

Application:

1. Rural Electrification

Supplies constant power to remote and off-grid locations where traditional grid infrastructure is not present. Solar and wind are used as main sources, with hydro and storage providing stability.

2. Smart Grids & Microgrids

Facilitates decentralized energy generation with improved grid stability and reduced transmission losses.

Batteries or pumped hydro storage stabilize supply and demand variations.

3. Industrial Power Supply
Applied in mining, manufacturing, and large-scale industrial processes needing constant power.
Hybrid systems lower fuel reliance and operating expenses.

4.Irrigation Systems for Agriculture
Powers irrigation systems and water pumps in farms, lowering diesel generator dependency. Can utilize Hydro if streams are present, and storage facilitates nighttime runtime.
5. Island & Coastal Towns
Lower dependency on costly diesel fuel for power generation.
Daytime power is provided by wind and solar, and hydro and batteries smooth out supply.
6. Military & Power Backup during Emergencies
Guarantees stable power for distant military camps, disaster relief shelters, and emergency response centers.
Enhances energy security through multiple sources of generation.

VI. CONCLUSION

A Hybrid Renewable Energy System (HRES) incorporating solar, wind, and hydro power offers a clean, stable, and efficient means of generating electricity. The use of multiple sources enables the system to exploit their complementary characteristics solar for day-time energy, wind for intermittency in generation, and hydro for reliable base-load supply providing permanent and balanced energy output. The integration addresses the intermittence issues of each individual renewable source, enhancing the stability of the grid, security of energy, and overall efficiency of the system. Though the initial installation expenses may be prohibitive, long-term advantages like diminished dependency on fossil fuels, decreased greenhouse gas emissions, and energy resilience ensure that hybrid systems are the strategic choice for clean energy transformation.
With the evolution in smart grids, energy management systems, and better efficiency of renewable technologies, solar-wind-hydro hybrid systems provide a bright direction towards sustainable energy development and a low-carbon future

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