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Article

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Impact of climate conditions on the integration and performance of solar and wind hybrid systems in residential microgrids

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Abstract

The increasing deployment of renewable energy systems (RES) with battery storage requires careful consideration due to their multiple advantages, including low-cost electricity, clean energy generation, and improved reliability and stability of power supply. However, variations in solar irradiance and wind speed can significantly affect energy production in hybrid microgrids. Battery systems help compensate for these fluctuations, ensuring consistent energy availability. This study investigates the integration and performance of solar, wind hybrid systems with battery storage in residential microgrids under varying climate conditions. The findings highlight the importance of climate-aware design to optimize energy yield, enhance reliability, and maximize the benefits of renewable energy integration.

Keywords: Hybrid Renewable Energy System (HRES), Solar-Wind Hybrid System, Residential Microgrids, Battery Energy Storage System (BESS), Renewable Energy Integration, Climate Impact Analysis, Distributed Energy Resources (DER)

1 Introduction

In isolated and rural locations, hybrid renewable energy systems (HRES) are becoming a viable solution to the problem of unreliable electricity [1]. The generation patterns of

solar and wind energy sources are complimentary, with solar energy peaking during the day and wind energy frequently increasing at night or during the winter. By combining both of them, they decrease intermittency, increase reliability, and minimize the need for large storage systems [2].

By storing excess energy during times of high generation and delivering it when renewable output decreases, Battery Energy Storage Systems (BESS) improve microgrid performance. In order to guarantee steady power delivery in hybrid microgrids, BESS additionally permits load shifting, peak shaving, and frequency regulation [3].

Azerbaijan has a high renewable potential, with average solar irradiation of 4–5.4 kWh/m^2 and favorable wind conditions in coastal and elevated areas. Hybrid microgrids can reduce fossil-fuel dependency, support distributed generation, and enable electrification in remote communities [4].

In this study MATLAB/Simulink is used to model PV and wind subsystems with the BESS, and simulate a parallel microgrid configuration. Key metrics, including load sharing, voltage stability, and power balance, are analyzed to evaluate the technical feasibility and performance of hybrid solar-wind microgrids in Azerbaijan [2, 3]. The integration of the PV, wind and BESS units is shown in Fig. 1.



Fig. 1 PV, wind and BESS integration into the microgrid

Purpose of the Study: The main purpose of this research is to investigate the technical feasibility, dynamic performance, and reliability of hybrid solar-wind energy systems for residential microgrids in Azerbaijan. This study aims to evaluate how variable solar irradiance (W/m^2) and wind speed (m/s) affect the power output (W) of both PV and wind subsystems, and how the integration of Battery Energy Storage Systems (BESS) can maintain stable voltage (V) and current (I) under fluctuating renewable generation. Furthermore, the research examines the overall system efficiency and energy output (E, kWh), as well as the load sharing and power balancing between parallel energy sources to ensure a reliable and continuous electricity supply for local communities. One of the most important aspects of the study is the evaluation of environmental benefits, particularly the potential reduction of CO_2 emissions

through decreased reliance on fossil-fuel generation. By quantifying the avoided greenhouse gas emissions, this research highlights the role of hybrid solar-wind microgrids in mitigating climate change, improving local air quality, and promoting sustainable energy transitions in Azerbaijan. The results are intended to provide insights into the practical implementation of hybrid renewable microgrids, their contribution to energy security, and their long-term environmental and economic benefits for residential and community-scale applications.

The symbols and units of measurement for the parameters given in the article are provided in Table 1.

Table 1 Symbols and units of measurement for parameters

Symbol	Description
A [m^2]	Area swept by wind turbine blades
G [W/m^2]	Solar irradiance on the surface
η	Efficiency of the system
P [W]	Power output
v [m/s]	Wind speed
ρ [kg/m^3]	Air density
C_p	Power coefficient of the wind turbine
R [Ω]	Resistance
I [A]	Electric current
V [V]	Voltage
T [°C]	Temperature
E [kWh]	Energy output

2 Methodology

The operation of a hybrid renewable energy system (HRES) in a residental microgrid setting is evaluated in this study using a simulation-based methodology. MATLAB/Simulink, a flexible platform for modelling nonlinear systems and simulating the dynamic response of electrical power networks, was used for both modelling and simulations [5, 6]. Photovoltaic (PV) arrays, wind turbines, battery energy storage systems (BESSs), inverters, and step-up transformers are all part of the system under study. It is a 110 kV microgrid that is connected to a 100 MW central station. The simulation period was one hour, and both solar irradiance and wind speed were varied every 15 minutes.

The annual energy generation from the solar PV and wind power plants was used to calculate the saved CO_2 emissions in order to evaluate the environmental benefits of the planned hybrid renewable energy system (HRES). In accordance with IPCC and IEA standards, the analysis used standard emission factors for conventional fossil fuel-based generation [6–8].

The following formula was used to determine each renewable subsystem's yearly energy production [6]:

$$E = P_{\text{rated}} \times \text{CF} \times 8760. \tag{1}$$

For 10 MW solar PV plants, assuming a representative capacity factor of 18% ($CF_{\text{PV}} = 0.18$), the annual generation is given by [7]:

$$E_{\text{PV}} = 10 \times 0.18 \times 8760 = 15{,}768 \text{ MWh/year}. \tag{2}$$

Similarly, for the 20 MW wind farm, using an average capacity factor of 30% ($CF_{\text{Wind}} = 0.30$), the annual energy generation is [6, 7]:

$$E_{\text{Wind}} = 20 \times 0.30 \times 8760 = 52{,}560 \text{ MWh/year}. \tag{3}$$

Therefore, the total annual renewable energy output from the hybrid system is expressed as [6]:

$$E_{\text{Total}} = E_{\text{PV}} + E_{\text{Wind}}. \tag{4}$$

$$E_{\text{Total}} = 15{,}768 + 52{,}560 = 68{,}328 \text{ MWh/year}.$$

This total renewable energy output represents the amount of electrical energy that would otherwise have been produced by conventional fossil-fuel power plants.

3 Discussion of the results

This section presents the detailed simulation results of the photovoltaic (PV), wind, and battery energy storage system (BESS) subsystems developed in MATLAB/Simulink. The purpose of this analysis is to evaluate the electrical and dynamic responses of each renewable source under varying solar irradiance, wind speed, and load conditions.

As described in Section 2, the simulation period was one hour, during which both solar irradiance and wind speed were varied every 15 minutes. The analysis focuses on voltage, current, power, and control dynamics to validate the accuracy of the models and the robustness of the control strategies implemented. The Simulink schematic of the system is shown in Fig. 2.

The single-diode equivalent circuit, which represents nonlinear I–V and P–V behaviour under varying irradiance and temperature, was used to model the 10 MW photovoltaic subsystem. The temperature was kept at 30 °C while the irradiance profile was changed from 1200 W/m^2 → 1300 W/m^2 → 1400 W/m^2 → 1200 W/m^2.

The power curve of the PV system before the inverter (Fig. 3) represents the DC-side performance of the solar array, showing how the output power varies directly with solar irradiance. The curves are based on DC power measurements obtained before the inverter stage, reflecting the raw generation capability of the PV modules. Considering the system's rated output of 10 MW at 1000 W/m^2 irradiance (under Standard Test Conditions, STC), the simulation results indicate that the peak DC power increases to approximately 14 MW at 1400 W/m^2 and decreases to around 12 MW at 1200 W/m^2.

The power curve of the photovoltaic (PV) system measured after the transformer (Fig. 4) exhibits a linear correlation between power output and solar irradiance. As the

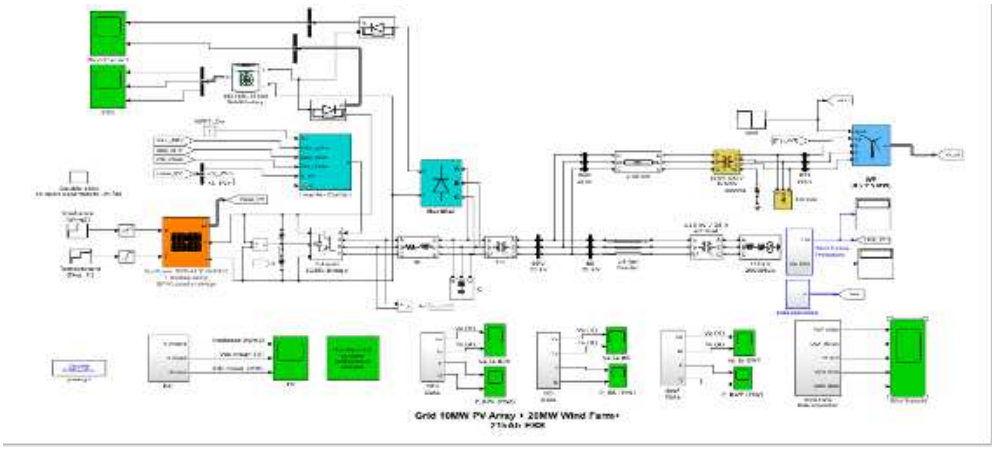


Fig. 2 Simulink schematic of the hybrid renewable energy system (HRES) integrating a 10 MW solar PV plant, 20 MW wind farm, and 10 MW battery energy storage system (BESS) connected to a 35 kV bus and linked to a 110 kV grid via a 47 MVA system transformer [9, 10]

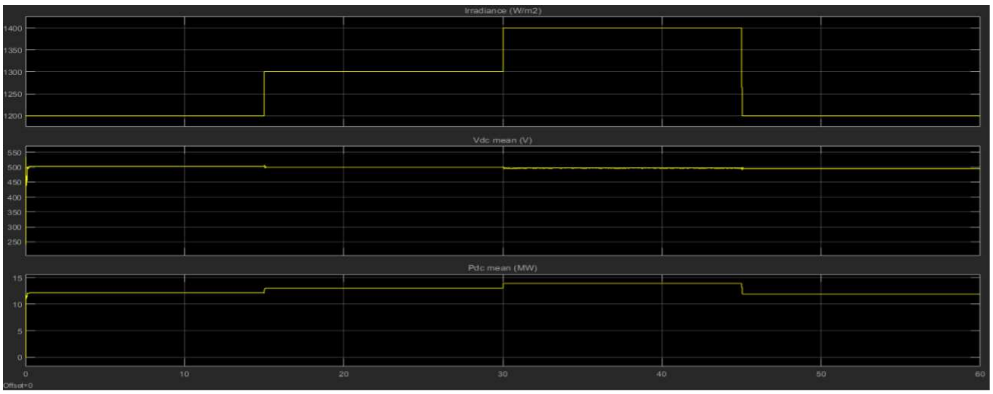


Fig. 3 PV power output corresponding to solar irradiance (before PV inverters)

irradiance increases, the system's power output rises proportionally, reaching a peak of approximately 9.85 MW at an irradiance level of 1400 W/m^2. When the irradiance decreases to 1200 W/m^2, the corresponding output power drops to around 7.8 MW. This behavior clearly indicates the effective operation of the Maximum Power Point Tracking (MPPT) algorithm, which continuously adjusts the operating point of the PV system to extract maximum available power under varying irradiance conditions [11].

The system bus voltage and current waveforms of the PV subsystem were examined in order to verify the network integration performance, as shown in Fig. 5. The system's steady-state operating behaviour is represented by these graphs, which show the V–I characteristics following the PV power transformer. The inverter control strategy's successful operation and correct synchronisation with the 35 kV grid bus are confirmed by the findings, which show sinusoidal voltage and current waveforms with

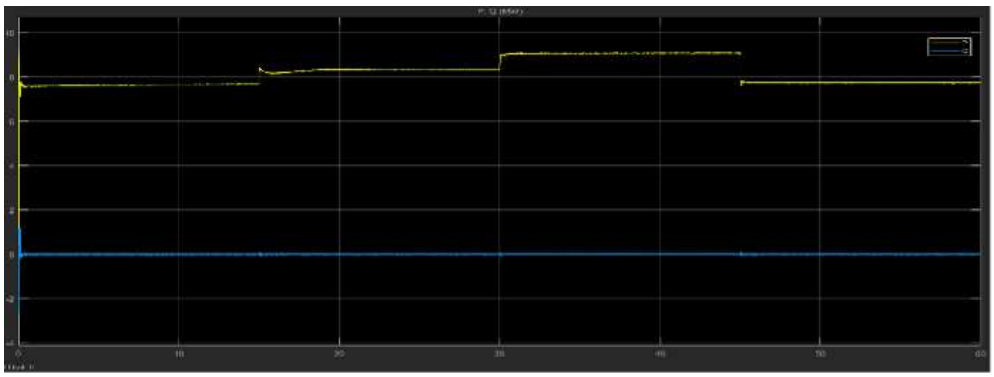


Fig. 4 PV power output as a function of solar irradiance (after inverters and PV transformer)

no distortion. Under typical operating settings, this behaviour shows efficient power transfer and stable grid interaction.

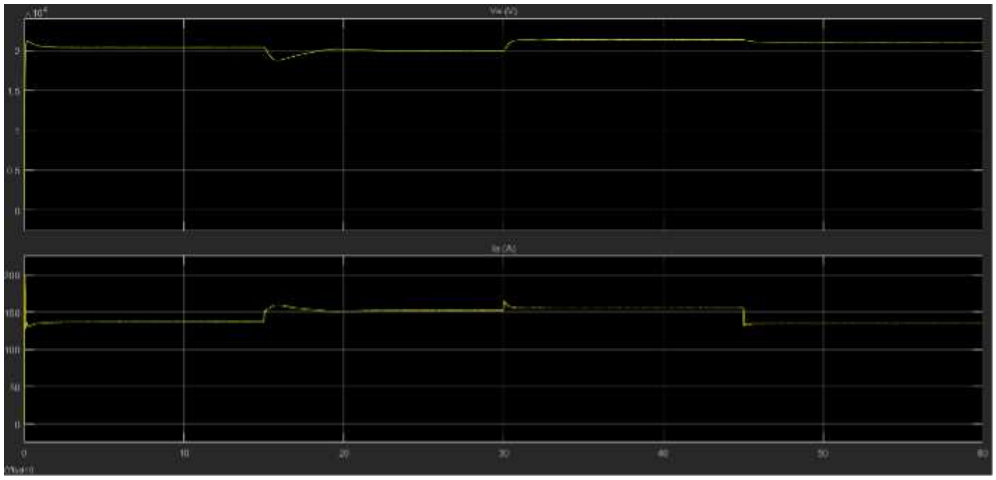


Fig. 5 PV system bus V–I characteristics

Fig. 6 shows the wind farm's dynamic response, which shows how turbine output power and blade pitch angle change as wind speeds do. The generated power grows in proportion to the wind speed, reaching the rated output of 2.5 MW per turbine at 12 m/s. In order to control aerodynamic efficiency and avoid rotor over-speeding, the pitch control system simultaneously modifies the blade angles. The pitch angle is adjusted to retain the best possible power capture when wind speed drops. These findings support the accuracy of the aerodynamic model's performance and the efficiency of the turbine's control system, guaranteeing the wind subsystem's steady and effective operation under fluctuating wind conditions [12].

The 10 MW Battery Energy Storage System (BESS) was modeled using a state-of-charge (SoC) dependent equivalent-circuit approach that supports bidirectional power

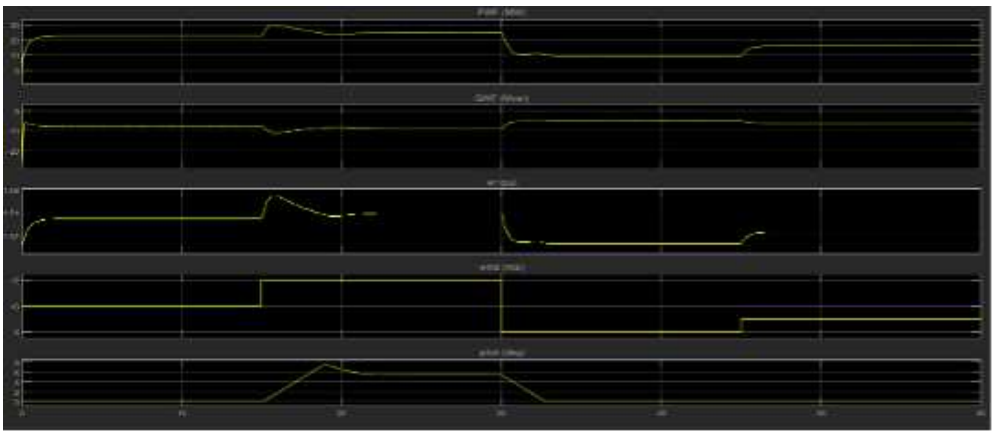


Fig. 6 Wind farm power output and pitch angle variations with wind speed (Simulink simulation, author's own work)

flow with the grid. The implemented control strategy enhances overall system stability by charging the battery during periods of high renewable generation and discharging it when solar and wind output decline.

Fig. 7 illustrates the dynamic behavior of the SoC, average battery current, and terminal voltage throughout the simulation. During the initial phase, the SoC steadily increases, showing that the BESS is absorbing excess renewable energy. In this period, the battery current is predominantly negative, corresponding to charging, while the terminal voltage gradually rises as stored energy accumulates.

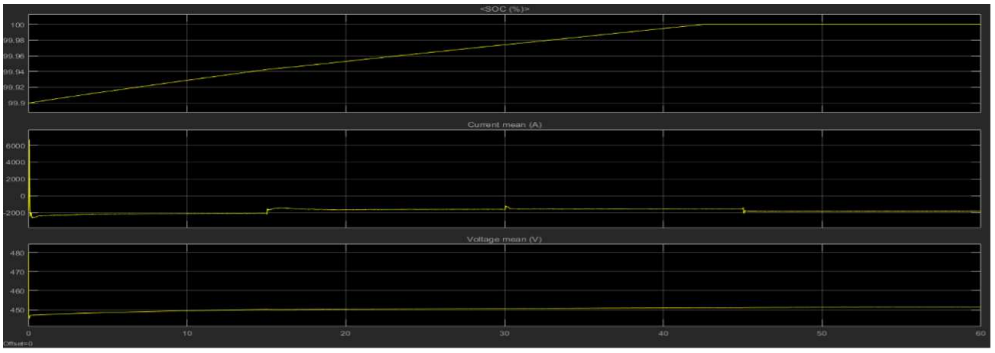


Fig. 7 BESS state-of-charge (SoC), current, and voltage profiles (Simulink simulation, author's own work)

To assess the power-sharing behavior of the hybrid renewable system, the total active (P) and reactive (Q) power delivered before the main step-up transformer was examined, as illustrated in Fig. 8.

Following the initial transient startup, the combined active power output from the PV and wind subsystems stabilizes at approximately 40 MW until the 15-minute mark. As renewable availability improves due to increased irradiance and wind speed

between 15–30 minutes, the total active power rises to a peak of roughly 50 MW. When resource conditions weaken between 30–45 minutes, system output declines to nearly 25 MW. During the final 45–60-minute interval, the active power recovers and stabilizes near 30 MW.

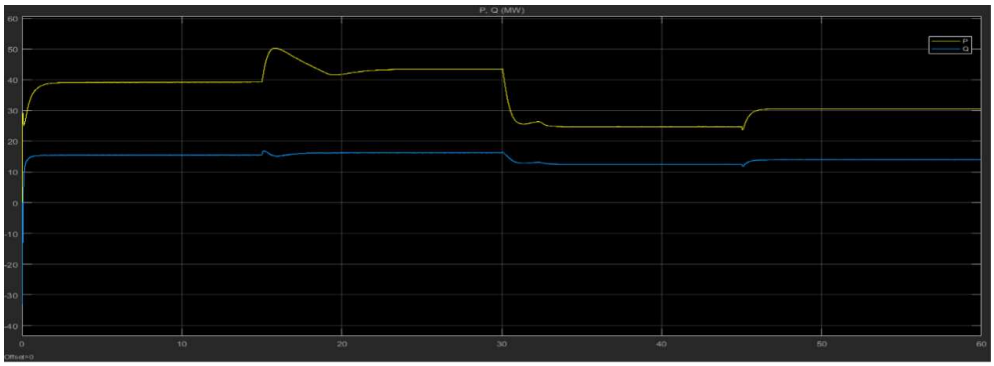


Fig. 8 Active and reactive power output of the hybrid renewable system (Simulink output, author's own work)

4 Results

The comprehensive simulation results indicate that the proposed hybrid renewable energy system maintains stable and reliable performance under realistic variations in environmental conditions. The dynamic responses of the PV subsystem show proportional changes in power generation as irradiance fluctuates, confirming the correct operation of the MPPT algorithm and efficient DC–AC conversion. Throughout the simulation, the inverter sustained well-regulated voltage and current outputs with minimal distortion, ensuring accurate synchronization with the grid.

The wind subsystem also demonstrated strong dynamic behavior, responding appropriately to variations in wind speed. The pitch control mechanism effectively limited turbine output during high wind conditions to prevent excess power production, while the Permanent Magnet Synchronous Generator (PMSG) delivered steady electrical characteristics throughout the operational period. These observations validate the robustness of both the mechanical and electrical control strategies applied in the wind farm model.

The BESS contributed significantly to mitigating power fluctuations associated with the intermittent nature of solar and wind resources. Its controlled charging and discharging cycles ensured power balance, supported renewable bus voltage regulation, and improved transient response during rapid changes in generation. The State-of-Charge (SoC) remained within safe operational limits, preventing deep discharge and over-charging, which promotes battery longevity and system reliability.

Overall, the simulation results confirm that the hybrid PV, wind, BESS system can deliver reliable and grid-compliant power under variable resource conditions. Its ability to compensate for fluctuations, and maintain stable electrical characteristics

highlights its potential as a viable solution for advancing microgrid applications and distributed renewable energy development in Azerbaijan's power sector [13].

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