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MODELING AND PERFORMANCE ASSESSMENT OF A HYBRID SOLAR–WIND ENERGY SYSTEM FOR RURAL AND INSTITUTIONAL ELECTRIFICATION USING MATLAB/SIMULINK

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Abstract: Reliable electricity supply remains a major requirement for rural and geographically dispersed communities, where conventional grid extension can be technically difficult and economically burdensome. This paper presents a MATLAB/Simulink-based modeling, simulation, and performance assessment of a hybrid solar–wind energy system developed in the uploaded thesis for Guru Nanak Dev Engineering College (GNDEC), Ludhiana, Punjab. The study combines photovoltaic generation, wind energy conversion, maximum power point tracking, power electronic converters, battery energy storage, and an inverter within an integrated renewable-energy architecture. Meteorological inputs include solar irradiation, wind speed, and ambient temperature, while an appliance-based institutional load profile represents academic, laboratory, hostel, administrative, and auxiliary demand. The reported results show that the hybrid configuration produces 4.5 kWh/day and 1,642 kWh/year, compared with 2.8 kWh/day and 1,022 kWh/year for solar PV alone and 1.9 kWh/day and 694 kWh/year for wind alone. The hybrid system also reduces the reported loss of power supply probability to 3.2%, compared with 12.5% for solar and 16.8% for wind. Its reported LCOE is ₹4.9/kWh, while solar and wind values are ₹5.8/kWh and ₹6.4/kWh, respectively. These results demonstrate the value of resource complementarity and integrated control for reliable decentralized electricity supply.

***Index Terms* -** Hybrid renewable energy; Solar PV; Wind energy; MATLAB/Simulink; Rural electrification

I. INTRODUCTION

1.1 Background

Electricity access is closely associated with social development, educational activity, healthcare, communication, agriculture, and small-scale economic operations. The uploaded thesis identifies rural and remote regions as particularly challenging because low population density, geographical isolation, long transmission distances, and infrastructure costs can make conventional grid extension unattractive. Traditional alternatives such as diesel generation also introduce recurring fuel requirements, environmental impacts, and logistical constraints. These conditions motivate decentralized renewable-energy systems capable of using locally available resources while reducing dependence on conventional generation [1,2].

Solar and wind resources are especially suitable for decentralized generation, but their individual variability limits the continuity of standalone systems. Solar production is concentrated during daylight hours and is affected by irradiation and temperature, whereas wind generation depends strongly on local wind conditions and seasonal variation. The thesis therefore proposes a hybrid architecture in which the two sources operate together. Their complementary availability can reduce generation gaps, improve supply continuity, and reduce the dependence on excessive storage or backup generation. The study uses GNDEC Ludhiana as a representative institutional case because the campus contains academic buildings, laboratories, hostels, residential facilities, and other loads with continuing electricity requirements.

1.2 Research Problem

The central research problem is the design of a hybrid solar–wind system that can respond to variable renewable resources and changing electricity demand without excessive cost or inadequate reliability. The thesis identifies four interconnected challenges: resource variability, optimal sizing of PV, wind, battery and converter components, power-management and reliability requirements, and techno-economic optimization. Incorrect sizing can lead either to overinvestment or to insufficient generation. Similarly, poor coordination between renewable sources, storage, converters, and load demand can increase energy deficits and reduce system usefulness. The thesis consequently considers indicators including energy generation, LPSP, system efficiency, LCOE, and NPC within a MATLAB/Simulink framework [3,4].

1.3 Research Objective

The research objective is to develop and assess a comprehensive MATLAB/Simulink model of a hybrid solar–wind energy system using location-related meteorological inputs and a representative institutional load profile. The work aims to model PV and wind conversion, implement MPPT and power-conditioning stages, integrate battery storage, combine the renewable outputs through a common DC link, and evaluate the resulting system under changing operating conditions. A further objective is to compare the standalone solar, standalone wind, and hybrid configurations using numerical indicators of generation, capacity factor, reliability, LPSP, LCOE, and NPC. The broader purpose is to determine whether the hybrid arrangement provides a technically and economically stronger basis for decentralized rural and institutional electrification [5,6].

2. Literature Review

2.1 Solar–Wind Modeling and Control

The literature reviewed in the thesis establishes MATLAB/Simulink as an important platform for representing renewable-energy conversion processes. Ofualagba and Ubeku developed a mathematical basis for wind-energy conversion-system modeling, including wind-speed-dependent torque and power behavior [7]. Ahmad and Abdul-Hussain used MATLAB/Simulink to represent wind-turbine-generator dynamics and evaluate electrical responses [1]. Kumar and Shivashankar examined hybrid solar–wind operation with emphasis on maximum power extraction and reliability, reporting that appropriate sizing and control are important for reducing intermittency [5]. The thesis also discusses MPPT methods for solar and wind systems, including Perturb and Observe, Incremental Conductance, Tip Speed Ratio, and intelligent-control approaches. These studies support the use of source-specific controllers followed by a coordinated hybrid power-conditioning structure.

2.2 Hybrid Systems, Storage, and Optimization

Hybrid renewable systems have also been investigated from sizing, reliability, and economic perspectives. Sebbagh and Zaatri studied optimal sizing of a hybrid renewable system for a rural clinic and emphasized the importance of jointly selecting renewable and storage capacities [8]. Al-Turjman et al. evaluated solar PV–wind hybrid feasibility for household applications, highlighting the value of techno-economic assessment [2]. Roy et al. reviewed wind–solar hybrid configurations and sizing strategies, emphasizing the complementary behavior of the two resources [6]. Mulumba and Farzaneh examined an off-grid solar–wind–battery–flywheel configuration and linked storage selection with short- and long-duration power management. Across the reviewed work, the thesis identifies continuing needs for location-specific resource modeling, multi-objective optimization, dynamic control, and improved storage sizing. The present work addresses these needs through a unified MATLAB/Simulink model for the selected GNDEC case study.

3. Methodology

3.1 Site, Resource Data, and Load Profile

The selected study site is Guru Nanak Dev Engineering College, Ludhiana, Punjab, located at approximately 30.86° N and 75.85° E. The thesis describes the site as representative of an institutional demand environment containing academic buildings, laboratories, hostels, administrative blocks, and auxiliary facilities. Solar irradiation, wind speed, and ambient temperature are the principal meteorological variables. The thesis methodology states that daily data were obtained from the NASA POWER database and processed using Excel and MATLAB. The solar variable used is ALLSKY_SFC_SW_DWN, wind speed is specified at 10 m height (WS10M), and ambient temperature is represented by T2M. Missing, erroneous, and inconsistent values were screened before monthly and annual averages were developed. For the load, an appliance-based estimation method was used because high-resolution campus-wide smart-meter data were not available. Lighting, fans, air conditioners, computers, laboratory equipment, projectors, pumps, and other loads were combined into a 24-hour institutional demand profile.

3.2 Mathematical and Simulink Modeling

The PV energy model reported in the thesis is expressed as $E = A \times G \times \eta \times PR$, where E is daily energy output, A is panel area, G is solar irradiation, η is PV efficiency, and PR is the performance ratio. A single-diode/equivalent-circuit representation is used to generate PV voltage, current, and power characteristics, with irradiance and temperature included as inputs. The wind subsystem is based on aerodynamic relationships involving wind speed, air density, rotor swept area, power coefficient, tip-speed ratio, torque, and rotational speed. Both renewable subsystems use power-conditioning stages and MPPT control. The wind turbine is coupled to a generator, while the PV and wind outputs are combined through a common DC link.

3.3 Integration, Simulation, and Optimization

The complete Simulink structure contains PV and wind subsystems, DC–DC converters, a battery energy-storage subsystem, control blocks, a common DC bus, an inverter, and an LC filter. The battery stores surplus renewable energy and supplies the load during low-generation periods. Simulation records include renewable power, DC-bus voltage, inverter output, battery state of charge, unmet demand, and surplus energy. The optimization objective is to balance reliability, renewable utilization, and cost by considering PV capacity, wind-turbine rating, battery capacity, inverter specifications, LPSP, NPC, and LCOE. The thesis describes iterative evaluation through MATLAB optimization capabilities and evolutionary approaches, followed by comparison of candidate configurations.

4. Present Work

4.1 Case-Study Configuration

The present work develops a hybrid renewable-energy model for the GNDEC Ludhiana case study. The reported single-line configuration contains a 500 W solar PV source and a 500 W wind turbine, giving a combined installed renewable capacity of 1.0 kW. The PV source produces DC power directly from solar irradiation, while the wind subsystem produces electrical power that is conditioned before connection to the common DC bus. Separate DC–DC conversion stages regulate the source outputs and support maximum power extraction. The aggregated DC power is then converted to AC through an inverter for local load supply and grid interaction. The reported transformer ratio is 0.69/22 kV for grid interfacing. This arrangement provides a unified power path in which solar and wind resources can support one another during periods of resource reduction.

4.2 Meteorological Resource Assessment

The resource assessment shows strong solar potential at the selected location. The results chapter reports annual average solar irradiation generally around 4.8–5.0 kWh/m²/day, with maximum monthly values reaching approximately 7.35 kWh/m²/day in May–June and winter values falling to roughly 2.2–3.1 kWh/m²/day. The reported wind resource is more moderate: annual average wind speed is generally within 1.45–1.75 m/s, while maximum monthly averages reach about 2.60 m/s. Temperature varies substantially between seasons, from approximately 10–12°C in winter to 35–38°C during summer. These variations are important because PV output depends on both irradiance and module temperature, while wind output is strongly dependent on wind speed.

The thesis contains a results table covering solar irradiation, temperature, and wind speed for a long period, while the methodology section describes an 11-year extraction period. Because the uploaded document contains both descriptions, this paper does not alter or reconcile the source record; the numerical findings reported here are reproduced from the thesis results chapter. For example, the solar annual averages reported for 2015–2024 are 4.9152, 4.9872, 4.9862, 4.9351, 4.8226, 4.9747, 4.8607, 4.9104, 4.8562, and 4.7971 kWh/m²/day, respectively. The corresponding data demonstrate that the solar resource remains within a comparatively narrow annual range despite seasonal variation.

4.3 Hybrid Energy Contribution

Table 1 summarizes the monthly hybrid energy contribution reported in the thesis. Solar generation is the dominant component throughout the year, but wind makes a substantial complementary contribution during the monsoon and summer period. Solar generation ranges from 140 kWh in December to 195 kWh in May. Wind generation ranges from 68 kWh in February to 120 kWh in July. The largest monthly hybrid energy value is 284 kWh in June, followed by 283 kWh in May and 280 kWh in July. The annual total is 3,047 kWh, consisting of 1,987 kWh from solar and 1,060 kWh from wind. Thus, the reported annual contribution is 65.2% solar and 34.8% wind. The highest wind contribution occurs in July at 42.9%, followed closely by August at 42.8%, illustrating the complementary seasonal behavior of the two sources.

Month	Solar (kWh)	Wind (kWh)	Hybrid (kWh)	Solar (%)	Wind (%)
January	145	72	217	66.8	33.2
February	152	68	220	69.1	30.9
March	175	75	250	70.0	30.0
April	188	82	270	69.6	30.4
May	195	88	283	68.9	31.1
June	182	102	284	64.1	35.9
July	160	120	280	57.1	42.9
August	158	118	276	57.2	42.8
September	168	105	273	61.5	38.5
October	176	86	262	67.2	32.8
November	148	74	222	66.7	33.3
December	140	70	210	66.7	33.3
Annual Total	1987	1060	3047	65.2	34.8

Table 1. Monthly and annual hybrid solar–wind energy contribution reported in the thesis.

4.4 Dynamic PV and Wind Model Behavior

The PV model demonstrates a transient response during initialization followed by stable operating regions. The reported PV voltage initially settles near 18–20 V, rises to approximately 23–24 V at about 0.3 s, and reaches approximately 25–26 V at 0.6 s. Current initially stabilizes near 15 A, then rises to around 20 A and finally 22–23 A. The corresponding power increases from about 250 W to approximately 400 W and then nearly 500 W. These step changes represent improved operating conditions and MPPT movement toward a new maximum power point. The wind model shows a comparable dynamic response. Its voltage initially stabilizes around 18–19 V and increases to approximately 22–23 V near 0.3 s. Reported wind power increases from roughly 220–250 W initially to about 350–380 W and subsequently to 450–480 W as wind conditions improve. These responses demonstrate that the source models can represent changing operating conditions and that the control structure can extract additional available renewable power.

4.5 Comparative System Performance

The thesis directly compares standalone solar PV, standalone wind, and the combined hybrid system. The solar and wind installations are each rated at 0.5 kW, whereas the hybrid configuration has 1.0 kW combined capacity. Average daily generation is reported as 2.8 kWh/day for solar, 1.9 kWh/day for wind, and 4.5 kWh/day for the hybrid system. Annual generation is 1,022 kWh/year, 694 kWh/year, and 1,642 kWh/year, respectively. The hybrid configuration also achieves the lowest LPSP at 3.2%, compared with 12.5% for solar and 16.8% for wind. Although the hybrid NPC is reported as ₹10.5 lakh, higher than the standalone values of ₹8.2 lakh and ₹9.1 lakh, its LCOE is the lowest at ₹4.9/kWh compared with ₹5.8/kWh for solar and ₹6.4/kWh for wind. The system is consequently classified as having high reliability and excellent suitability for rural electrification in the thesis.

Performance Parameter	**Solar PV**	**Wind**	**Hybrid Solar–Wind**
Installed capacity (kW)	0.5	0.5	1.0
Average daily energy (kWh/day)	2.8	1.9	4.5
Annual energy (kWh/year)	1022	694	1642
Capacity factor (%)	23.3	15.8	18.7
Peak power output (W)	500	500	1000
LPSP (%)	12.5	16.8	3.2
LCOE (₹/kWh)	5.8	6.4	4.9
NPC (₹ lakh)	8.2	9.1	10.5
Reliability	Moderate	Moderate	High
Night availability	No	Yes, if wind available	Yes
Storage requirement	High	High	Moderate
Rural electrification suitability	Good	Good	Excellent

Table 2. Comparison of solar, wind, and hybrid system performance reported in the thesis.

5. Results and Discussion

The numerical results indicate that the hybrid configuration provides the strongest overall balance between energy production and supply reliability. The combined system produces 4.5 kWh/day on average, which is 1.7 kWh/day higher than solar alone and 2.6 kWh/day higher than wind alone. On an annual basis, the hybrid output of 1,642 kWh/year is 60.7% higher than the reported solar-only generation of 1,022 kWh/year and 136.6% higher than the wind-only generation of 694 kWh/year. The hybrid LPSP of 3.2% is substantially below the standalone values of 12.5% and 16.8%, indicating fewer periods in which demand cannot be adequately supplied.

The monthly contribution results further explain this improvement. Solar provides 65.2% of annual hybrid energy, while wind supplies 34.8%. During July and August, wind contributions reach 42.9% and 42.8%, respectively, reducing dependence on solar generation. The dynamic simulations also demonstrate controlled increases in source power as environmental conditions improve: PV power rises from approximately 250 W to nearly 500 W, while wind power rises from approximately 220–250 W to 450–480 W. Economically, the hybrid system reports the lowest LCOE at ₹4.9/kWh, despite a higher NPC of ₹10.5 lakh. Taken together, the results support the thesis conclusion that resource complementarity, MPPT control, and storage integration improve the suitability of the hybrid arrangement for decentralized electricity supply.

6. Future Scope

• Real-time validation: collect measured solar irradiance, wind speed, ambient temperature, and campus load data to validate the simulated model.

• Advanced multi-objective optimization: apply methods such as Particle Swarm Optimization, Genetic Algorithm, Harris Hawks Optimization, or NSGA-II to jointly optimize cost, reliability, emissions, and renewable utilization.

• Intelligent MPPT and energy management: investigate ANN, fuzzy-logic, and adaptive controllers for faster tracking under rapidly changing irradiance and wind conditions.

• Advanced energy storage: compare lithium-ion, flow batteries, supercapacitors, flywheels, and hybrid battery–supercapacitor configurations with the existing storage model.

• Experimental implementation: develop a laboratory or field-scale prototype to verify the MATLAB/Simulink predictions and assess practical power-quality and operating constraints.

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