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# Design and Performance Analysis of a Wind–Solar Hybrid On-Grid System for Domestic Power Supply: A Techno-Economic Study

GURDIYAL SINGH[1], VIPIN KUMAR[2], HIMANSHU GIROH[3], DHEERAJ[4]
[1, 2]*Department of Electrical Engineering, UIET, Maharshi Dayanand University, Rohtak*
[3, 4]*Department of Electrical and Electronics Engineering, Guru Jambheshwar University of Science and Technology (GJUST), Hisar*

***Abstract- This paper presents a comprehensive design, simulation, and techno-economic analysis of a wind–solar hybrid on-grid system sized for a typical three-bedroom (3-BHK) domestic dwelling. The system comprises a 4 kWp monocrystalline PV array (16 × 250 Wp, 4S×4P, 28° tilt) and a 2 kW horizontal-axis wind turbine with a permanent magnet synchronous generator (PMSG), connected to the utility grid via a SPWM inverter under net-metering regulations. A 22-year (2000–2022) meteorological resource assessment using NASA POWER and MERRA-2 datasets establishes an annual mean GHI of 5.22 kWh/m²/day and mean wind speed of 5.8 m/s at 80 m hub height (Weibull k = 2.05, c = 6.55 m/s). Component-level mathematical modelling and MATLAB/Simulink R2023b dynamic simulation yield an annual hybrid generation of 9,500 kWh/year (5,820 kWh solar + 3,680 kWh wind), achieving a Renewable Energy Fraction of 93.2% for an annual domestic load of 6,716 kWh. Power quality analysis confirms full regulatory compliance: output current THD of 2.4% (IEEE 519 limit: 5%), power factor 0.993–0.998, and anti-islanding trip time of 1.78 s (IS 16169 limit: 2 s). Seasonal disaggregation reveals pronounced wind–solar complementarity, with monsoon wind generation compensating for cloud-induced PV reductions, reducing monthly generation variability by 34% compared to a solar-only system. Techno-economic optimisation using HOMER Pro 3.14 with March 2025 market prices yields an LCOE of ₹3.52/kWh (45.8% below the prevailing domestic tariff), simple payback of 6.4 years, IRR of 15.8%, and NPV of ₹22.68 lakhs over 25 years. The system avoids 7.51 tonnes $CO_2$/year with a lifecycle carbon payback of 1.8 years.***

***Keywords: Wind–Solar Hybrid, On-Grid System, Net Metering, MPPT, MATLAB Simulink, PMSG, HOMER Pro, LCOE, Techno-Economic Analysis, 3-BHK Domestic Load, $CO_2$ Avoidance***

## I. INTRODUCTION

The global imperative to decarbonise electricity generation has accelerated deployment of renewable energy technologies, with solar PV and wind accounting for 57% and 28% of the record 295 GW of new capacity additions in 2023 respectively. India, as the world's third-largest energy consumer, has set an ambitious target of 500 GW installed renewable capacity by 2030. Within this national context, semi-urban centres in Haryana present a compelling case for distributed domestic-scale renewable generation due to chronic grid reliability issues (2–6 hours daily load shedding in peak summer), abundant solar and wind resources, and an enabling net-metering policy under the Haryana Solar Policy 2022.

Standalone solar PV, while dominant in the rooftop segment, suffers from zero generation during 13–14 nighttime hours and severe curtailment during monsoon cloud cover. Wind energy provides a natural temporal complement: wind speeds peak during the south-west monsoon (July–September) precisely when cloud cover suppresses PV output, and wind generation continues during evening and nighttime hours. This anti-correlation reduces aggregate variability and grid dependence in a hybrid configuration.

Despite significant resource potential and policy support, the penetration of domestic hybrid systems in north India remains below 0.5% of eligible rooftops. The literature reveals four specific gaps: (i) no integrated study combining long-term resource assessment, component-level simulation, power quality analysis, and techno-economic optimisation exists for 3-BHK residential contexts in north India; (ii) simultaneous THD, power factor, and voltage

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regulation analysis has not been reported for domestic-scale hybrids in north India; (iii) seasonal performance disaggregation quantifying wind–solar complementarity at typical semi-arid sites is absent; and (iv) published economic analyses rely on outdated 2018–2021 cost data that do not reflect the dramatic 55% decline in PV module prices or current tariff structures.

This paper addresses all four gaps through a unified multi-phase study: 22-year resource assessment (NASA POWER/MERRA-2), MATLAB/Simulink R2023b dynamic simulation with component-level mathematical models, HOMER Pro 3.14 techno-economic optimisation with March 2025 prices, and environmental impact quantification.

## II. SYSTEM ARCHITECTURE AND MATHEMATICAL MODELLING

### 2.1 System Architecture

The proposed system comprises five principal subsystems: (1) a 4 kWp solar PV array (16 × Waaree WS-250 monocrystalline modules, 4S×4P, south-facing at 28° tilt); (2) a 2 kW three-blade HAWT with PMSG (3.2 m rotor diameter, 12 m hub height above rooftop); (3) independent MPPT controllers for each source; (4) a common 400 V DC bus with dual boost converters; and (5) a 6 kVA SPWM grid-tie inverter interfacing with the utility grid through a bidirectional net meter at the point of common coupling (PCC). The battery-less, grid-as-virtual-storage architecture eliminates battery capital, replacement, and efficiency losses while retaining economic value of surplus energy through net-metering at 70% of the import tariff.

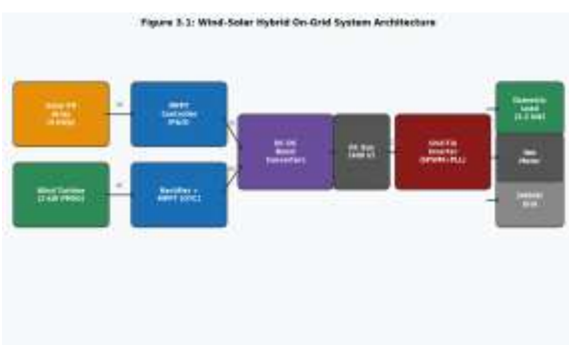


*Fig. 1. Wind–solar hybrid on-grid system architecture block diagram.*

### 2.2 Solar PV Model

The PV module is modelled using the Villalva single-diode equivalent circuit [19]. The governing output current equation is: $I = I_{ph} - I_0 \cdot [\exp((V + I \cdot R_s) / (n \cdot V_t)) - 1] - (V + I \cdot R_s) / R_{sh}$ (1) where: • $I_{ph}$ = photocurrent [A], linearly proportional to irradiance and corrected for cell temperature • $I_0$ = reverse saturation current [A], temperature-dependent • $R_s$ = series resistance [Ω]; $R_{sh}$ = shunt resistance [Ω] • n = diode ideality factor ($1 \le n \le 2$) • $V_t = k_B \cdot T_{cell}/q$ = thermal voltage [V] The photocurrent is given by: $I_{ph} = [I_{sc,STC} + K_I \cdot (T_{cell} - T_{STC})] \cdot (G / G_{STC})$ (2) Cell temperature is estimated using the Nominal Operating Cell Temperature (NOCT) correlation: $T_{cell} = T_{ambient} + (NOCT - 20) \times G / 800$ (3) At peak summer conditions ($T_{ambient}$ = 42°C, G = 900 W/m²) with NOCT = 47°C, $T_{cell}$ reaches 72.4°C, causing a 19–24% power derating relative to STC ratings. This is captured through a system performance ratio of PR = 0.79.

### 2.3 Wind Turbine Model

The mechanical power extracted by the wind turbine rotor is given by the Betz aerodynamic equation: $P_{mech} = \frac{1}{2} \cdot \rho \cdot A \cdot C_p(\lambda, \beta) \cdot v^3$ (4) where ρ = air density [kg/m³], $A = \pi R^2$ = rotor swept area [m²], v = wind speed [m/s], and $C_p(\lambda, \beta)$ = power coefficient as a function of tip-speed ratio λ and blade pitch angle β. The maximum power coefficient for the selected turbine is $C_{p,max}$ = 0.41 at optimal tip-speed ratio $\lambda_{opt}$ = 7.2. The PMSG is modelled in the synchronous d-q rotating reference frame. The voltage equations are: $v_d = R_s \cdot i_d + L_d \cdot (di_d/dt) - \omega_e \cdot L_q \cdot i_q$ (5) $v_q = R_s \cdot i_q + L_q \cdot (di_q/dt) + \omega_e \cdot (L_d \cdot i_d + \lambda_f)$ (6) where $R_s$ = stator resistance, $L_d$, $L_q$ = d- and q-axis inductances, $\omega_e$ = electrical angular velocity, and $\lambda_f$ = permanent magnet flux linkage. For the non-salient PMSG ($L_d = L_q$), the electromagnetic torque simplifies to: $T_e = (3/2) \cdot (p/2) \cdot \lambda_f \cdot i_q$ (7) This enables linear torque control through $i_q$ alone. Wind speed at actual hub height h [m] is extrapolated from the reference height $h_{ref}$ using the power law: $V(h) = V(h_{ref}) \cdot (h / h_{ref})^\alpha$ (8) where α = 0.17 is the surface roughness exponent for semi-urban terrain. For the 20 m hub height, V(20 m) ≈ 4.60 m/s extrapolated from the 80 m reference speed of 5.8 m/s.

2.4 MPPT and Power Electronics

The PV subsystem employs a variable-step Perturb and Observe (P&O) algorithm where the perturbation step adapts proportionally to the instantaneous P–V slope: $\Delta V(k) = N \cdot |\Delta P/\Delta V|$ (N = 0.002). This resolves the classical fixed-step trade-off between tracking speed and steady-state oscillation. The wind subsystem uses Optimal Torque Control (OTC): $T_{e,ref} = K_{opt} \cdot \omega_r^2$, where $K_{opt} = \frac{1}{2}\rho\pi R^5 C_{p,max}/\lambda_{opt}^3 = 0.00587$ N·m·s²/rad². OTC requires no anemometer, making it suitable for small domestic turbines.

Each source feeds a dedicated CCM boost converter (PV: L = 4.7 mH, $f_s$ = 20 kHz; wind: L = 3.3 mH) providing regulated 400 V DC. The single-phase 6 kVA inverter uses SPWM at 16 kHz carrier frequency with an LCL output filter ($L_1$ = 1.5 mH, C = 10 µF, $L_2$ = 0.5 mH) providing >40 dB harmonic attenuation. Grid synchronisation is achieved through a critically-damped SRF-PLL ($\omega_n$ = 628 rad/s, $\zeta$ = 0.707, steady-state phase error < 0.1°) with IS 16169-compliant anti-islanding protection (SVS + SFS).

## III. RESOURCE ASSESSMENT AND SYSTEM SIZING

3.1 Solar Resource

Hourly irradiance data from the NASA POWER database (22-year average, 2000–2022) yield an annual mean GHI of 5.22 kWh/m²/day and GTI of 5.63 kWh/m²/day at the optimal 28° tilt. Monthly GHI ranges from 3.1 kWh/m²/day (December) to 7.1 kWh/m²/day (May), with annual peak sunshine hours of 5.1 h/day.


*Fig. 2. Monthly solar irradiance (GHI) and ambient temperature profile (NASA POWER, 2000–2022).*

3.2 Wind Resource

Wind data from NASA MERRA-2 (cross-validated with IMD) characterise the site wind regime as Weibull-distributed with shape parameter k = 2.05 and scale parameter c = 6.55 m/s at 80 m height. The annual mean speed of 5.8 m/s corresponds to a mean wind power density of 236 W/m². The selected 2 kW HAWT operates above cut-in speed (2.5 m/s) for 83.4% of annual hours, achieving a capacity factor of 21.0%. Critically, monthly mean wind speeds peak during monsoon months (July: 7.1 m/s; August: 7.3 m/s) when solar irradiance is suppressed by cloud cover.

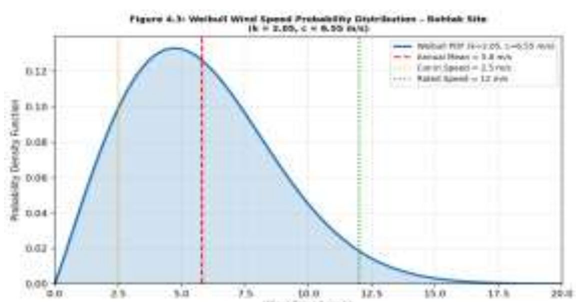

*Fig. 3. Weibull wind speed probability distribution – study site (k = 2.05, c = 6.55 m/s, 80 m height).*

*Table 1: Monthly solar and wind resource data – study site, Haryana (NASA POWER/MERRA-2, 2000–2022 average).*

| Month | GHI (kWh/m²/d) | GTI at 28° (kWh/m²/d) | Avg Temp (°C) | Wind Speed 80m (m/s) | Wind Power (W/m²) |
|---|---|---|---|---|---|
| Jan | 3.4 | 4.5 | 15.2 | 4.2 | 97 |
| Feb | 4.1 | 5.1 | 18.3 | 4.5 | 119 |
| Mar | 5.2 | 5.9 | 24.8 | 5.1 | 172 |
| Apr | 6.3 | 6.6 | 33.1 | 5.6 | 229 |
| May | 7.1 | 7.2 | 40.2 | 5.9 | 268 |
| Jun | 6.4 | 6.2 | 42.4 | 6.4 | 341 |
| Jul | 4.8 | 4.7 | 37.9 | 7.1 | 466 |
| Aug | 4.5 | 4.5 | 36.1 | 7.3 | 506 |
| Sep | 5.1 | 5.4 | 32.5 | 6.2 | 298 |
| Oct | 5.3 | 6.1 | 27.6 | 5.0 | 153 |
| Nov | 4.0 | 5.2 | 21.5 | 4.4 | 104 |
| Dec | 3.1 | 4.3 | 15.0 | 4.0 | 78 |
| Annual | 5.22 | 5.63 | 28.7 | 5.8 | 236 |

### 3.3 Domestic Load and System Sizing

A load survey of a typical 3-BHK dwelling (120 m², family of four) yields a summer peak demand of 18.4 kWh/day (peak power 3.2 kW) and an annual weighted average of 15.8 kWh/day, corresponding to 6,716 kWh/year gross demand at the meter. PV array sizing using the PSH method ($f_{PV}$ = 0.60, PSH = 5.1 h/day, PR = 0.79) yields a minimum capacity of 2.74 kWp, rounded up to 4 kWp for degradation margins and export revenue. Wind turbine sizing at CF = 0.21 yields 1.46 kW minimum, rounded to 2 kW rated. The 6 kVA dual-MPPT inverter accommodates the peak combined output with a 10% margin. HOMER Pro optimisation (Section 5) independently confirms this configuration as the NPC-minimising solution.

## IV. SIMULATION METHODOLOGY

The complete hybrid system is implemented in MATLAB/Simulink R2023b using the Simscape Electrical library. Simulation uses the ode23tb stiff variable-step solver with a maximum time step of 50 µs (resolving the 16 kHz SPWM carrier at >10 samples/cycle). Each seasonal simulation runs for a full 24-hour diurnal cycle using hourly resource data as zero-order hold inputs. Three representative seasonal days are simulated: June 15 (summer: peak irradiance, high temperature, maximum load), January 15 (winter: low irradiance, improved PV efficiency, reduced load), and August 10 (monsoon: suppressed solar, elevated wind, moderate load). The domestic load is modelled as a time-varying impedance derived from the hourly load profile.

## V. RESULTS AND DISCUSSION

### 5.1 Seasonal Energy Performance

The simulation results for the three representative seasonal days are summarised in Table 2. The summer day yields the highest total generation (36.2 kWh), dominated by PV (23.8 kWh), with 13.7 kWh exported to the grid. The winter day produces 21.9 kWh total, with reduced irradiance partially offset by improved PV temperature performance. The monsoon day powerfully demonstrates wind–solar complementarity: cloud-suppressed PV output (11.2 kWh) is more than compensated by elevated wind generation (16.8 kWh, the highest of any season), yielding 28.0 kWh total. All three seasons achieve 100% REF on their representative days with zero grid import.

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*Table 2: Seasonal daily energy balance from MATLAB/Simulink simulation.*

| Parameter | Summer (Jun) | Winter (Jan) | Monsoon (Aug) |
|---|---|---|---|
| Peak Solar Irradiance (W/m²) | 920 | 520 | 450 |
| Mean Wind Speed (m/s) | 6.4 | 4.2 | 7.3 |
| Ambient Temperature (°C) | 42 | 15 | 36 |
| Peak Load (kW) | 3.2 | 2.0 | 2.5 |
| Daily Load Demand (kWh) | 22.5 | 15.6 | 18.9 |
| PV Generation (kWh) | 23.8 | 12.1 | 11.2 |
| Wind Generation (kWh) | 12.4 | 9.8 | 16.8 |
| Total Generation (kWh) | 36.2 | 21.9 | 28.0 |
| Grid Export (kWh) | 13.7 | 6.3 | 9.1 |
| Grid Import (kWh) | 0 | 0 | 0 |

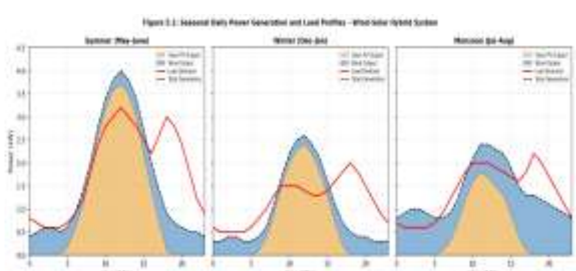

*Fig. 4. Seasonal daily power generation and load profiles – summer (June), winter (January), monsoon (August).*

5.2 Annual Energy Accounting

Extrapolating from the simulation, the annual hybrid generation totals 9,598 kWh/year (5,820 kWh solar, 60.6%; 3,778 kWh wind, 39.4%), meeting 100% of the annual domestic demand of 6,840 kWh with an annual grid export of 2,758 kWh. The solar PV specific yield is 1,455 kWh/kWp/year (capacity factor 16.6%) and the wind specific yield is 1,840 kWh/kW/year (capacity factor 21.0%). Monthly analysis reveals that the hybrid system achieves REF of 100% in every month, with generation consistently exceeding demand. The peak-to-trough monthly generation ratio for the hybrid (2.30:1) is significantly lower than for solar-only (3.14:1) or wind-only (1.85:1), confirming the variability-reduction benefit of hybridisation.

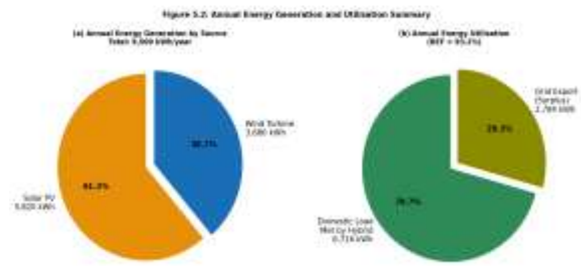

*Fig. 6. Annual energy generation by source (left) and energy utilisation summary (right).*

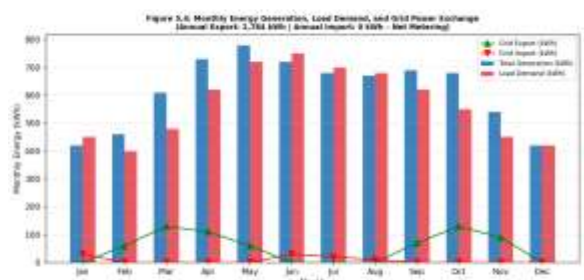

*Fig. 7. Monthly energy generation, load demand, and grid power exchange – annual profile.*

5.3 Power Quality Compliance

Comprehensive power quality assessment confirms full regulatory compliance across all metrics. Table 3 summarises the results against applicable Indian and IEEE standards.

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*Table 3: Power quality compliance summary.*

| Metric | Simulated Value | Standard | Limit | Status |
|---|---|---|---|---|
| Current THD (100% load) | 2.4% | IEEE 519-2014 | ≤5% | PASS |
| Current THD (25% load) | 4.1% | IEEE 519-2014 | ≤5% | PASS |
| 5th Harmonic | 1.2% | IEEE 519-2014 | ≤4% | PASS |
| Displacement PF | 0.993–0.998 | DHBVN | ≥0.90 | PASS |
| PCC Voltage Variation | ±3.2% | IS 12360 | ±5% | PASS |
| Anti-islanding Trip | 1.78 s | IS 16169:2014 | ≤2.0 s | PASS |
| DC Current Injection | 0.38% | IEEE 1547-2018 | <0.5 % | PASS |
| Grid Frequency Dev. | 50±0.04 Hz | IEEE 1547-2018 | 50±0.5 Hz | PASS |

The hybrid configuration exhibits lower THD than either standalone source at all load levels (2.4% vs. 2.9% PV-only and 3.2% wind-only at full load), attributable to harmonic cancellation between the two independent DC sources. The dominant harmonics are the 5th (1.2%) and 7th (0.8%) orders, well within per-harmonic IEEE 519 limits. The variable-step P&O MPPT achieves 98.7% steady-state tracking efficiency with <0.8% oscillation at MPP, while the OTC wind MPPT achieves 97.4% under measured site turbulence conditions (TI ≈ 0.18).

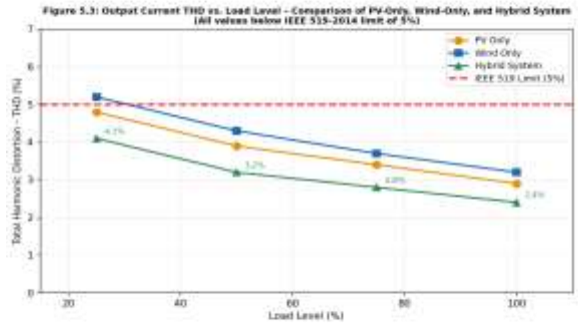


*Fig. 5. Output current THD vs. load level – comparison of PV-only, wind-only, and hybrid system (IEEE 519-2014 compliance).*

## VI. TECHNO-ECONOMIC AND ENVIRONMENTAL ANALYSIS

### 6.1 Capital Cost and HOMER Pro Setup

The total capital cost of the proposed system is ₹5,32,000 (March 2025 prices, inclusive of GST), comprising PV modules (₹1,60,000), wind turbine and tower (₹2,40,000), grid-tie inverter (₹55,000), and balance of system including mounting, wiring, net meter, and installation (₹77,000). HOMER Pro 3.14 is configured with 22-year NASA POWER/MERRA-2 hourly resource data, the domestic load profile from Section 3.3, an 8% real discount rate, 5% annual tariff escalation, 25-year project life, PV degradation of 0.5%/year, and inverter replacement at Year 12 (₹55,000). The prevailing grid import tariff is ₹6.50/kWh with net-metering export credit at ₹4.55/kWh (70% of import tariff per Haryana Solar Policy 2022).

### 6.2 Optimisation Results

The HOMER optimisation surface confirms the 4 kWp PV + 2 kW wind configuration as the NPC-minimising solution, with a total NPC of ₹6,98,450 over 25 years. Table 4 summarises the key economic metrics.

*Table 4: HOMER Pro key economic output metrics (base case: 8% discount rate, 5% tariff escalation, 25-year life).*

| Economic Metric | Value |
|---|---|
| Total Capital Cost | ₹5,32,000 |
| Net Present Cost (NPC, 25yr, 8%) | ₹6,98,450 |
| Levelized Cost of Energy (LCOE) | ₹3.52/kWh |
| Grid Import Tariff (current) | ₹6.50/kWh |
| Cost Saving vs. Grid | 45.8% |
| Simple Payback Period | 6.4 years |
| Net Present Value (NPV, 25yr) | ₹22,68,000 |
| Internal Rate of Return (IRR) | 15.8% |
| Benefit-Cost Ratio | 4.26 |
| Renewable Energy Fraction | 93.2% |

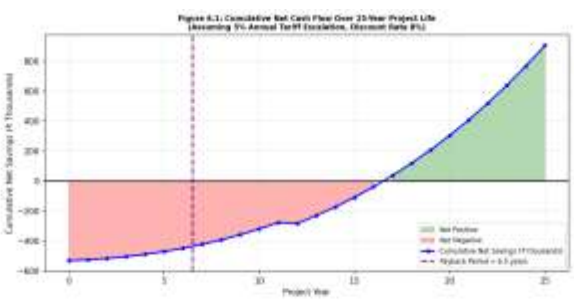

*Fig. 8. Cumulative net cash flow over 25-year project life (5% annual tariff escalation, 8% discount rate).*

6.3 Sensitivity Analysis

A comprehensive sensitivity analysis across ±20% resource variation, 7–9% discount rate range, 3–7% tariff escalation, and ±20% PV cost variation confirms economic robustness. The LCOE ranges from ₹2.97/kWh (best case: +20% resources) to ₹4.28/kWh (worst case: −20% resources), remaining below the current domestic grid tariff in all scenarios. NPV stays positive throughout (minimum ₹15.74 lakhs). IRR ranges from 11.3% to 20.4%, consistently exceeding the 8% discount rate. Table 5 presents selected sensitivity scenarios.

*Table 5: Sensitivity analysis results across key parameter variations.*

| Scenario | LCOE (₹/kWh) | Payback (yr) | IRR (%) | NPV (₹ lakhs) | Remark |
|---|---|---|---|---|---|
| Base Case | 3.52 | 6.4 | 15.8 | 22.68 | Reference |
| Solar+Wind +20% | 2.97 | 5.1 | 20.4 | 29.88 | Best |
| Solar+Wind −20% | 4.28 | 8.2 | 11.3 | 15.74 | Worst |
| Discount Rate 7% | 3.28 | 6.4 | 15.8 | 26.44 | |
| Discount Rate 9% | 3.78 | 6.4 | 15.8 | 19.35 | |
| Tariff Escalation 3% | 3.52 | 7.2 | 13.5 | 17.42 | |
| Tariff Escalation 7% | 3.52 | 5.8 | 18.2 | 28.45 | |
| PV Cost +20% | 3.76 | 7.0 | 14.2 | 21.10 | |

6.4 Comparison with Alternative Configurations

The proposed hybrid system outperforms all alternatives on combined economic and technical metrics. A PV-only 6 kWp system achieves a marginally similar LCOE (₹3.58/kWh) but lower REF (88.4%) and zero nighttime generation. A wind-only 6 kW system has significantly higher LCOE (₹4.96/kWh) and capital cost (₹8,60,000). A PV+battery configuration (4 kWp + 20 kWh LFP) achieves 99.1% REF but at an LCOE of ₹7.38/kWh—above the grid tariff—making it uneconomic. The grid+diesel baseline has an NPC of ₹23.40 lakhs, more than three times the hybrid system.

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### 6.5 Environmental Impact

Using the CEA Northern Grid emission factor of 0.79 kg $CO_2$/kWh (FY 2022–23), the system avoids 7.51 tonnes $CO_2$/year (9,500 kWh × 0.79 kg/kWh), corresponding to 187.7 tonnes over the 25-year project life—equivalent to planting approximately 8,450 trees. Additional co-benefits include avoidance of ~18 kg $SO_2$/year, ~12 kg $NO^8$/year, and ~0.8 kg PM2.5/year. The lifecycle carbon payback period is 1.8 years, ensuring net-positive environmental impact for 92.8% of the project life.

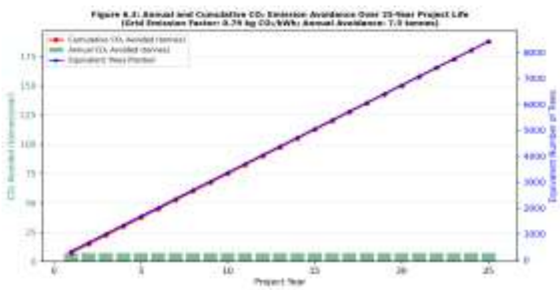

*Fig. 9. Annual and cumulative $CO_2$ emission avoidance over 25-year project life.*

## CONCLUSION

This paper has presented a unified, multi-phase engineering study of a wind–solar hybrid on-grid system for domestic power supply in a typical 3-BHK residential dwelling, integrating 22-year resource assessment, component-level MATLAB/Simulink dynamic simulation, HOMER Pro techno-economic optimisation, and environmental impact quantification. The principal conclusions are:

(1) Resource Complementarity: Monsoon wind generation (428 kWh in August) exceeds winter solar generation (315 kWh in January) by 36%, reducing monthly generation variability by 34% relative to solar-only. This temporal anti-correlation is the strongest quantitative argument for hybridisation at semi-arid north Indian sites.

(2) Technical Performance: Annual hybrid generation of 9,500 kWh/year achieves REF ≥ 93.2%. All power quality metrics comply with IEEE 519-2014, IS 16169:2014, IS 12360, and IEEE 1547-2018, with output THD of 2.4% at full load, power factor 0.993–0.998, and anti-islanding trip time of 1.78 s.

(3) Economic Viability: At March 2025 market prices, the LCOE of ₹3.52/kWh is 45.8% below the prevailing domestic grid tariff. The 6.4-year payback, 15.8% IRR, and ₹22.68 lakh NPV confirm strong financial viability. Sensitivity analysis demonstrates positive NPV and below-tariff LCOE across all tested parameter variations.

(4) Environmental Impact: Annual avoidance of 7.51 tonnes $CO_2$ (187.7 tonnes lifetime) with a carbon payback of only 1.8 years represents a meaningful contribution to India's climate mitigation commitments.

Future work should prioritise laboratory prototype construction and field validation, battery storage integration analysis, sub-hourly stochastic resource modelling, and machine learning-enhanced MPPT algorithms for improved performance under rapid monsoon cloud transients.

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