

Extended Thermo-economic Metrics and Sustainability Potential of Small Wind Energy Systems: A Case-Based Analysis

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Received: 10TH OCT 2025

Reviewed: 14TH NOV 2025

Accepted: 5TH DEC 2025

ABSTRACT

This study assesses wind energy potential across six locations in Cross River State, Nigeria, for small-scale Wind Energy Conversion Systems (WECS). Annual mean wind speeds ranged from 3.38 m/s at OGP1 to 5.3 m/s at OBUP5, with no site recording speeds below 3 m/s, indicating suitability for wind applications. Power and energy densities spanned 6.8-102.9 W/m² and 4.49-85.58 kWh/m², respectively, with the highest values at OBUP5 and AKP4. Exergy-based indicators were analysed; Bergey XL.1 showed a 70.37% increase in the Exergetic Sustainability Index (ESI), a 9.09% rise in Waste Exergy Ratio (WER), and a 33% gain in Useful Speed Volume (USV), demonstrating efficient airflow utilization. Proven-2.5 kW and Skystream-3.7 kW exhibited ESI increases of 46% and 52%, respectively. Exergetic equivalents of labour (*eel*) ranged from 43.36 MJ (OGP1) to 65.04 MJ (BKP3), while capital equivalents (*eec*) varied from 64.88 MJ/\$ to 80.11 MJ/\$. Cost of energy (COE) values ranged from \$0.063/kWh (BKP3, Proven-2.5 kW) to \$0.181/kWh (OBRP6, Skystream-3.7 kW), confirming both technical and economic viability.

Keywords: Exergetic Sustainability Index, Cost of Energy, Small-scale wind power.

I. INTRODUCTION

Assessing the long-term viability of power generation technologies requires evaluating thermodynamic efficiency in conjunction with broader sustainability metrics. Conventional exergy analysis quantifies the maximum theoretical work that a system can perform as it reaches equilibrium, thereby optimizing internal performance but neglecting externalities such as economic and environmental costs (1). Extended Exergy Accounting (EEA), referred to as Extended Thermo-economic in this study, addresses this by incorporating the exergy equivalents of labour, capital, and ecological impacts, thereby providing a systemic, second-law-based framework. The EEA has been applied in national energy policy in Norway (2) and the Netherlands (3) as well as in rural renewables in China (4) and Turkey's transport sector (5). Its application in wind energy remains limited,

although (6) demonstrated its value, showing efficiency differences of 63.82% (standard) versus 15.76% (EEA) for a utility-scale turbine. This study extends EEA to small-scale Wind Energy Conversion Systems (WECS) across various sites in Cross River State, Nigeria, integrating wind, labor, and capital data to evaluate performance and inform sustainable energy planning. Studies by (7) and (8) underscore the viability and sustainability potential of wind energy in Nigeria, providing essential data on wind speed variability and system integration impacts that inform extended thermoeconomic assessments of small wind energy systems. (9) highlight seed variety impacts, informing sustainability metrics in renewable energy studies.

II. METHOD

A. Description of Study Locations

This study examines six emerging economic hubs in Cross River State, Nigeria: Akamkpa, Obubra, Ikom, Ogoja, Boki, and Obudu. These hubs are driven by projects such as the Export Processing Zone, ecotourism growth, and a Mega Business Resort. These towns show strong potential for decentralized renewable energy, particularly small-scale wind systems. Wind speed data from the NIMET Calabar station (2014–2023) at a 10-meter height were analysed using mean values to assess wind resource indicators. Calculations of wind power density and kinetic energy flux confirmed site suitability for small-scale wind applications. These results support the viability of Wind Energy Conversion Systems (WECS) across the region's varied microclimates. Table 1 provides detailed site-specific data to guide EEA-based sustainability assessments.

B. Mathematical modelling

The Weibull Distribution Function (WDF) is used to model wind speed profiles at selected sites. Using the two-parameter PDF and CDF forms from (11) and (12), this approach provides an accurate characterization for wind energy resource assessment (Eqs. 1 and 2).

$$f_{(v)} = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (1)$$

$$F_{(v)} = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (2)$$

The general exergy balance equation for a control volume operating under steady-state conditions, while neglecting potential, kinetic, and electrical energy contributions, is formulated based on the works of (13), (14), and (15). This simplified

form is suitable for thermal and mechanical systems where such energy components are negligible relative to thermal exergy flows. The steady-state exergy balance is expressed as

$$\dot{E}x_{dest} = \sum_k \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W}_{cv} + \sum_i (n_i \dot{E}x_i) - \sum_e (n_e \dot{E}x_e) \quad (3)$$

The exergy analysis of WT is given by Patel [24] and [18]. $\dot{E}x_{kin,in} - \dot{E}x_{kin,out} - \dot{E}x_{gen} - \dot{E}x_{des} = 0$ (4)

The standard exergy efficiency can be computed and it is based on EEA and equivalent extended exergy, as presented in Eqs. (5-8)

$$\varphi_{ex} = \frac{E_{gen}}{E_{x_{kin,in}} - E_{x_{kin,out}}} \quad (5)$$

$$E_{x_M} + E_{x_{PHY}} + EE_C + EE_L + EE_{ENV} - E_{x_{GEN}} - E_{x_{DEST}} = 0 \quad (6)$$

$$E_{x_{PHY}} = E_{x_{kin,in}} - E_{x_{kin,out}} \quad (7)$$

$$EE_C = EE_K + EE_{O\&M} + EE_{ins} = (C_K + C_{O\&M} + C_{ins}) \times ee_c \quad (8)$$

The plant efficiency, based on the EEA methodology, is presented in Eq. 9. The sustainability index based on extended exergy is presented in Eq. 10, while the other sustainability indicators based on the standard exergy method are presented in Table 2. The selected WECS are presented in Table 3.

$$\psi_{EEA} = \frac{E_{x_{gen}}}{E_{x_{PHY}} + EE_L + EE_K + EE_{O\&M} + EE_{ins}} \quad (9)$$

$$S_{EEA} = \frac{1}{1 - \psi_{EEA}} \quad (10)$$

TABLE II: SUSTAINABILITY INDICATORS

<i>S/No</i>	<i>Equation</i>	<i>Sustainability indicator</i>	<i>Equation number</i>	<i>Reference</i>
1	$ESI = \frac{1}{1 - \psi_{Ex}}$	Exergetic sustainability index	38	(16)
2	$LOP = \frac{Ex_{LOSS}}{Ex_{out}}$	Lack of productivity	39	(17)
3	$WER = \frac{Ex_{LOSS}}{Ex_{in}}$	Waste exergy ratio	40	(18)
4	$EEE = \frac{WER}{\psi_{Ex}}$	Environmental effect factor	41	(19), (20)

TABLE III: TECHNICAL SPECIFICATIONS OF SELECTED WIND TURBINES (BWT, RRG, AND STR 2024) (21-22)

<i>Turbines</i>	<i>Rated power (kW)</i>	<i>Rotor diameter (m)</i>	<i>Cut-in-speed (m/s)</i>	<i>Rated speed (m/s)</i>	<i>Swept Area (m²)</i>	<i>Turbine cost (US\$)</i>
Bergey XL. 1	1.0	2.5	2.0	11	4.91	4864.86
Proven- 2.5 Kw	2.5	3.5	2.5	11	9.63	9705.96
Skystream -3.7 kW	1.8	3.7	3.0	11	10.76	6962.00
Southwest Whisper 500	7.5	4.5	3.5	11	15.91	9444.75
Bergey Excel 10 kW	10	6.7	3.0	13	35.27	55353.2

III. RESULTS AND DISCUSSIONS

Figure 1 shows monthly air current velocity and cumulative frequency for the studied zones. The lowest breeze speeds in March range from 3.53 to 3.90 m/s, while the minimum airflow strength is recorded in April, August, and February. No site experiences velocities below 3 m/s, indicating suitability for small-scale wind energy applications. The distribution peaks at higher speeds, tapering off below 2 m/s. Annual averages span 3.38–5.3 m/s. Power and energy densities range from 6.8–102.9 W/m² and 4.49–85.58 kWh/m², respectively. Yearly totals range between 48.31–85.58 W/m²/year and 151.50–747.39 kWh/m²/year. OBUP5 and AKP4 show the highest energy and power outputs, whereas

OBRP6, IKP2, and OGP1 demonstrate the lowest. Exergy-based sustainability indicators were assessed for various Wind Energy Conversion Systems (WECS) at the OGP1 site, selected for its typical performance profile. Metrics included the Exergetic Sustainability Index (ESI), Waste Exergy Ratio (WER), Lack of Productivity (LOP), and Environmental Effect Factor (EEE), as derived by (13). The Bergey XL.1 achieved a 70.37% rise in ESI and 9.09% in WER, alongside a 33% increase in Useful Speed Volume (USV), indicating improved airflow utilization. Though WER rose slightly, low Exergy Destruction (ExD) minimized overall losses. This trend was notable in Proven-2.5 kW and Skystream-3.7 kW, with ESI increases of 46% and 52%, respectively

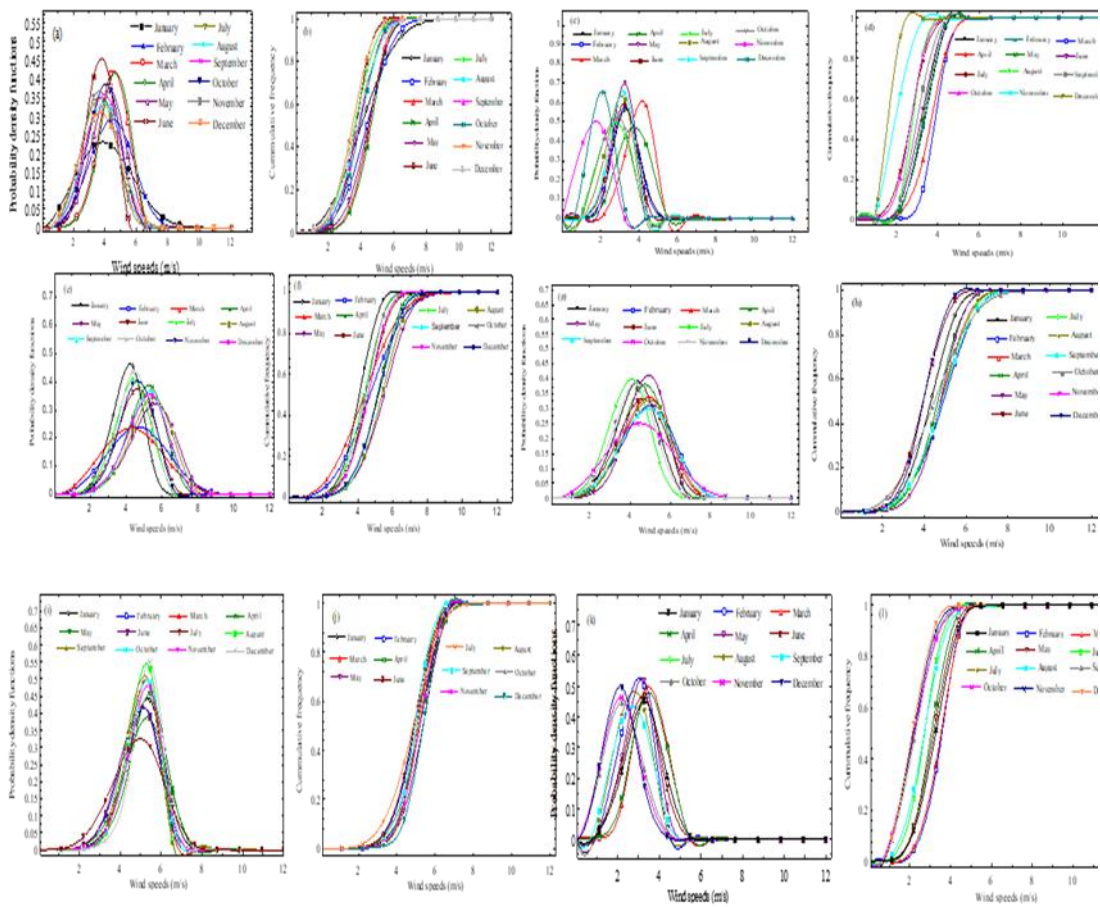


FIG.1. MONTHLY WSP PROBABILITY AND CUMULATIVE DENSITY DISTRIBUTION FOR THE LOCATIONS (A-B) OGP1, (C-D) IKP2, (E-F) BKP3, (G-H) AKP4, (I-J) OBUP5, (K-L) OBRP6

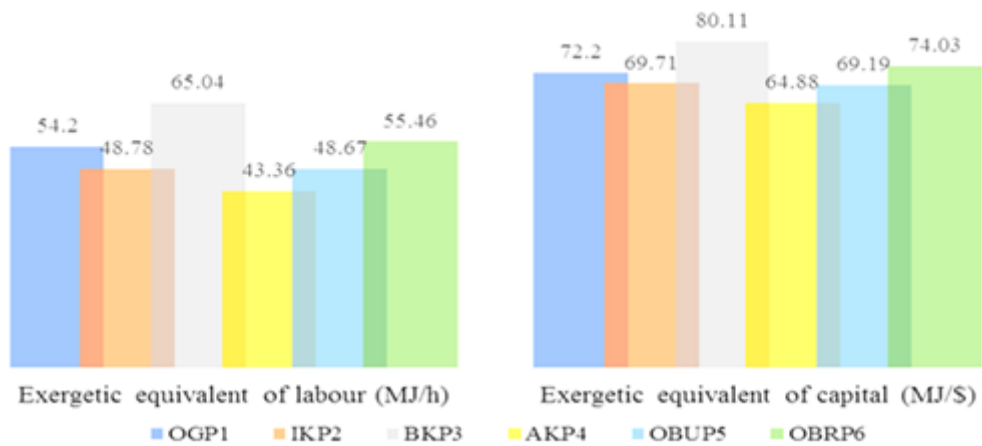


FIG 2. EXERGETIC EQUIVALENT OF LABOUR AND CAPITAL

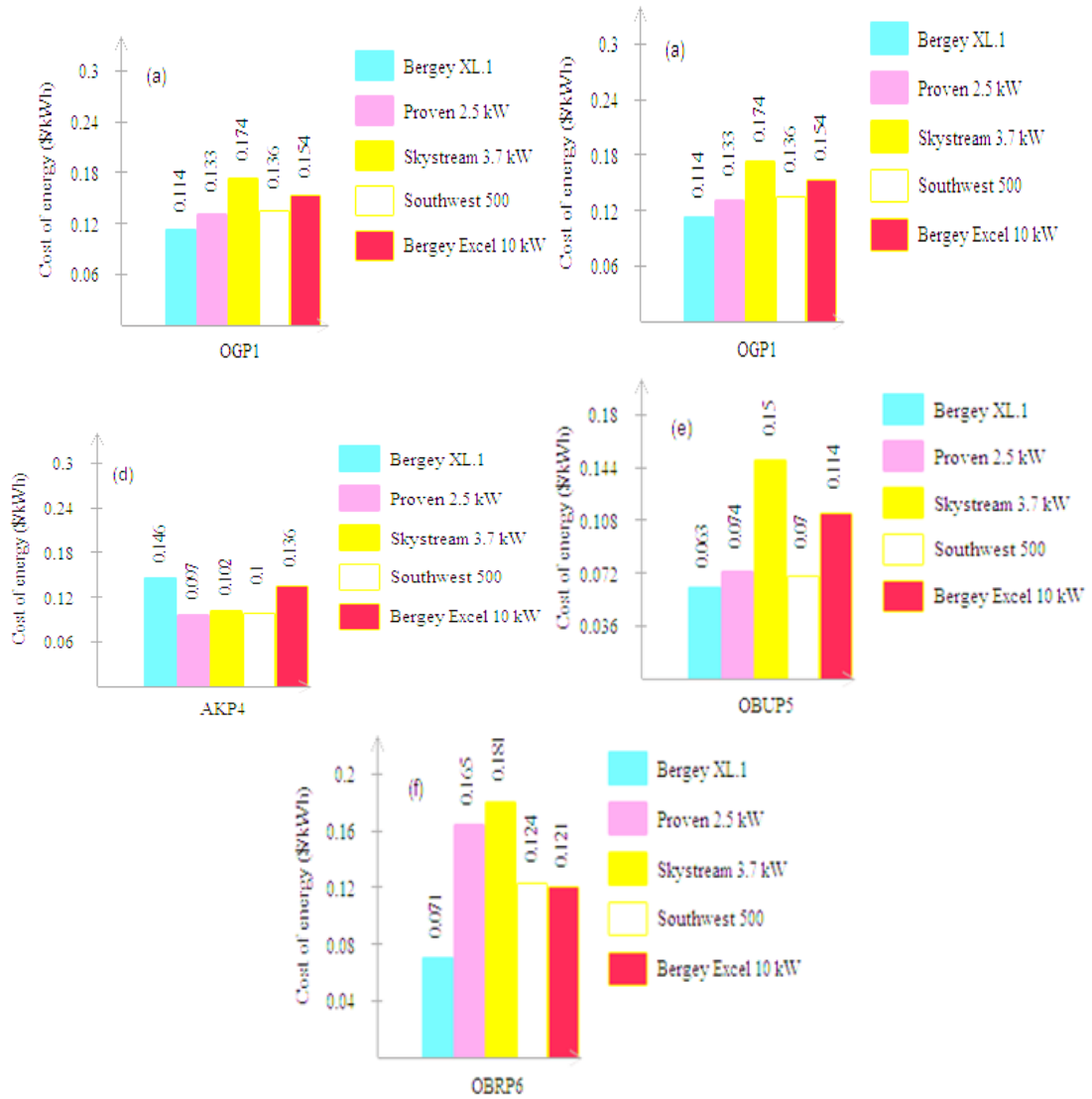


FIG.3. COST OF ENERGY PER KW FOR ALL WECS AND LOCATIONS (A) OGP1, (B) IKP2, (C) BKP3, (D) AKP4, (E) OBUP5, AND (F) OBRP6.

The ee_L vary from 43.36 MJ to 65.04 MJ, with BKP3

having the largest ee_L followed by locations OBRP6, OBUP5, OGP1, IKP2, AKP4 with values as shown in Fig.2 respectively. Similarly, the values of ee_C vary from 64.88 MJ/\$ to 80.11 MJ/\$. BKP3, OBRP6 and OGP1 has the highest ee_C of 80.11MJ/\$, 74.03MJ/\$ and 72.2MJ/\$ in that manner. However, the overall exergetic equivalent of labour is also determined by its quality and efficiency in consuming energy.

The energy cost (COE) per kilowatt-hour for various wind turbine systems across different sites was computed (Fig. 3). COE varies from \$0.063/kWh to \$0.181/kWh. At OGP1 (Fig. 3a), the lowest COE is \$0.114/kWh for Bergey XL.1, while Skystream 3.7 kW records the highest at \$0.1743/kWh. The COE variation between WECS at OGP1 is \$0.019/kWh (14.29%) between Bergey XL.1 and Bergey Excel 10 kW, and \$0.040/kWh (25.97%) between Bergey XL.1 and Bergey Excel 10 kW. In IKP2 (Fig. 3b), Bergey XL.1 and Southwest 500 have the minimum COE (\$0.082/kWh and \$0.1215/kWh). BKP3 (Fig. 3c) exhibits a COE range of \$0.0634–\$0.172/kWh,

with Bergey XL.1 bearing the highest cost. AKP4 (Fig. 73d) and OBUP5 (Fig. 3e) show encouraging COEs for specific turbines. OBRP6 reveals elevated COEs for all turbines except Bergey XL.1 (Fig. 3f).

Power and energy densities peaked at 102.9 W/m² and 85.58 kWh/m², while the lowest values, 6.8 W/m² and 4.49 kWh/m², were observed at OGP1. Exergetic sustainability metrics revealed that Bergey XL.1 achieved a 70.37% increase in ESI and a 33% improvement in USV at OGP1, accompanied by a

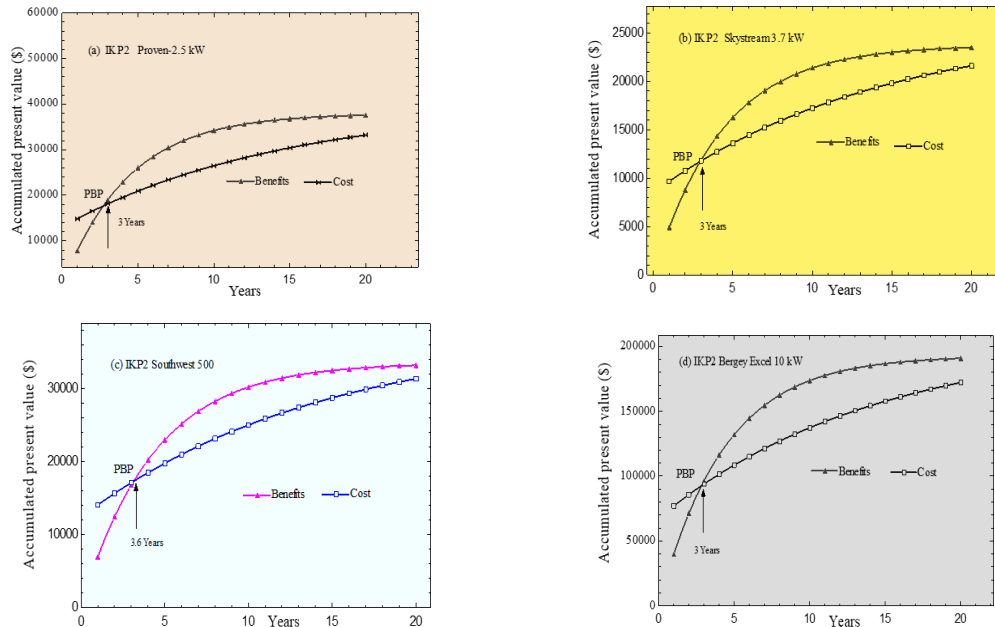


FIG.4 ECONOMIC PAYBACK OF INVESTMENT IN IKP2 FOR WECS (A) PROVEN-2.5 kW, (B) SKYSTREAM 3.7 kW, (C) SOUTHWEST 500, AND (D) BERGEY EXCEL 10 kW.

A. Estimated cost of investment and the Payback Period (PBP)

The repayment duration (PBP) refers to the timeframe required for a project to recover its initial capital outlay, excluding both its residual worth and the time-related value of money (23). Figure 4 illustrates the repayment durations for selected Wind Energy Conversion Systems (WECSs) across three sites: OGP1, IKP2, and BKP3, highlighting the feasibility of wind-based initiatives. At OGP1, the PBPs for the Proven-2.5 kW, Skystream 3.7 kW, Southwest 500, and Bergey Excel 10 kW are 4.2, 3.5, 3.2, and 4 years, respectively. At IKP2, the PBPs range from 3 to 3.6 years. For BKP3, the Bergey Excel 10 kW shows the maximum payback time of 5.6 years, followed by the Southwest 500 at 3.5 years. The analysis suggests encouraging prospects for investment

V. CONCLUSION

Quantitative analysis confirms strong potential for small-scale wind energy systems across Cross River State, Nigeria. All sites recorded annual mean wind speeds above 3 m/s, with OBUP5 (5.3 m/s) and AKP4 (5.1 m/s) outperforming the others.

minor 9.09% rise in WER due to minimal exergy destruction. Proven-2.5 kW and Skystream-3.7 kW also yielded notable ESI gains of 46% and 52%, respectively. Exergetic equivalents of labor (*eel*) ranged from 43.36 MJ to 65.04 MJ, with BKP3 recording the highest. Capital equivalents (*ec*) reached a maximum of 80.11 MJ/\$ at BKP3. The cost of energy (COE) varied significantly by site and system, ranging from \$0.063/kWh (Proven-2.5 kW at BKP3) to \$0.181/kWh (Skystream-3.7 kW at OBRP6). These findings validate WECS as a technically feasible and economically viable solution for rural electrification and localized energy generation in Nigeria

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