



## **Techno-Economic Feasibility of PV–Wind Hybrid Energy Systems in Low Wind Regimes: A Case Study of Ilaro, South-West Nigeria**

**<sup>1</sup>Zacchaeus Adetona, <sup>2</sup>Joel Ogunyemi and <sup>3</sup>Peter Mbamaluikem**

<sup>1,3</sup>Department of Electrical/Electronic Engineering  
Federal Polytechnic Ilaro (Now Federal University of Technology, Ilaro)

<sup>2</sup>Department of Renewable Energy Engineering  
Federal Polytechnic Ilaro (Now Federal University of Technology, Ilaro)

### **Abstract**

The persistent electricity deficit in Nigeria, particularly in the South-West region, necessitates sustainable and reliable energy alternatives such as solar and wind. However, the region is characterized by low wind regimes, limiting the effectiveness of standalone wind energy systems. Low wind speed will not overcome turbine inertia and thus the need for low cut-in speed wind turbines. The lack of studies in solar-wind hybrid system in South-West Nigeria also discourages any attempt at implementations. This study evaluates the techno-economic feasibility of a hybrid photovoltaic (PV)–wind energy system for Ilaro, Ogun State. A simulation-based analysis was carried out with HOMER and PVSyst with three configurations, namely PV-only, wind-only, and PV–wind hybrid. Input data includes local solar radiation data from the Nigerian Meteorological Agency (NIMET), wind speed profiles, and a mini community daily load demand of 250 kWh. Results show that while wind-only systems are economically unviable, integrating low cut-in wind turbines with PV significantly improves system reliability by reducing unmet load to approximately 2%, as compared to 7% for the PV-only system and 18% for the wind-only system. The hybrid system outperformed standalone systems with a COE of 202 N/kWh. The findings demonstrate that a properly designed hybrid PV–wind system is feasible and optimal for Nigeria's low-wind regions such as the South-West.

**Keywords:** Photovoltaic (PV)-wind hybrid system, techno-economic analysis, levelized cost of energy (LCOE), renewable energy, Ilaro, South-West Nigeria.

### **1. Introduction**

In many places around the world, sustainable living is the new recommended practice in many cities. City planners are finding ways to ensure resource sustainability (Hesami & Souzani, 2024)(Heidarzadeh et al., 2013). A major resource that is required for modern living is electric energy, and it is a scarce resource in many developing countries. To ensure a sustainable electric energy supply, renewable technologies have been developed and are being utilised for many possible applications today.

Nigeria is blessed with many renewable energy forms. These include tidal, hydro, wind, and solar energy. A deeper insight reveals that, among these, solar and hydro are yet to be tapped on a large scale. For the country to tackle the perennial energy insolvency, renewable energy needs



to be massively harnessed. From the south to northern Nigeria, solar is in abundance. Wind energy, on the other hand, is more viable in the north than in the south.

Wind energy potential has been widely studied for several locations in southern Nigeria, with consistent findings indicating low to moderate wind speed regimes. In designing a hybrid energy system rather than standalone wind installations, these characteristics must be taken into consideration.

The purpose of this study is to determine whether a PV–wind hybrid energy system is feasible in a low wind condition. In particular, it assesses the availability of resources, models system configurations, conducts techno-economic analysis using LCOE and NPC, and identifies the best configuration for a dependable and economical energy supply in Ilaro, South-West Nigeria.

## **2. South-Western Nigerian Solar-Wind Outlook**

### **2.1 Solar Irradiation Data**

The Southwestern Nigeria region lies within a humid tropical climate zone characterized by distinct wet and dry seasons, which strongly influence solar radiation availability. Early foundational studies conducted in Ibadan established that solar radiation follows predictable diurnal and seasonal patterns and can be estimated using empirical relationships involving sunshine duration and meteorological variables such as temperature and relative humidity (Adegoke et al., 1988; Akinola, 2007). These studies provided the basis for subsequent solar resource modeling across Nigeria.

Several recent studies confirm that Southwestern Nigeria despite significant seasonal variability, possesses moderate solar energy potential suitable for PV deployment. Long-term analyses using meteorological and satellite-derived datasets indicate that global horizontal irradiance (GHI) typically ranges between approximately 3.5 and 5.18 kWh/m<sup>2</sup>/day (Njoku & Ndefo, 2022). The months of December through March (dry season months) experience peak irradiation. Substantial reductions in irradiation are observed during the wet season (June–August) due to increased cloud cover and atmospheric moisture (Awomewe & Odunmorayo, 2024). This seasonal fluctuation has important implications for solar PV system deployment.

Other experimental and location-specific studies further illustrate the solar variability. Solar radiation data measured in Osogbo show peak values of approximately 16.59 MJ/m<sup>2</sup>/day and minimum values as low as 8.98 MJ/m<sup>2</sup>/day during the rainy season (Yusuf et al., 2017). Similarly, long-term observations in Ibadan reveal a pronounced reduction in solar radiation intensity during the third quarter of the year, corresponding to peak rainfall periods (Akinola, 2007). Thus, the availability of solar energy has been shown to have strong dependence of solar irradiation on regional climatic conditions.

Generally, southern Nigeria receives ~3.19 – 4.85 kWh/m<sup>2</sup>/day (Njoku et al. 2026) which is lower than northern Nigeria due to humidity and cloud cover. The regional average is 3.5 – 5.18 kWh/m<sup>2</sup>/day while Nigeria overall has 3.19 – 6.69 kWh/m<sup>2</sup>/day. Thus, it is clearly seen that the southwest lies in the moderate solar zone (Njoku et al., 2026). Table 1 shows typical annual



monthly average for the southwest. This data is further illustrated in Figure 1, showing the two monthly extremes and the peak and lowest months of the year. The following solar irradiation data are gleaned from literature: For Osogbo, the peak is  $\sim 4.6 \text{ kWh/m}^2/\text{day}$  in March; minimum is  $\sim 2.5 \text{ kWh/m}^2/\text{day}$  in August (Yusuf et al., 2017).

Njoku & Ndefo (2022) reported  $3.5\text{--}5.18 \text{ kWh/m}^2/\text{day}$  across Southwest Nigeria, including Ogun State regions, confirming moderate solar availability for PV systems. Similar seasonal variation patterns in nearby Southwestern cities with strong wet-season reduction due to cloud cover were reported by Yusuf et al. (2017). Akinola (2007) showed that solar radiation in Southwestern Nigeria follows a strong seasonal cycle, peaking in dry months and dropping significantly during rainy periods.

A report on ERA5 satellite-based analysis in Ogun State (Ewekoro–Ilaro axis) by Ayara et al. (2025) shows solar irradiance of  $\sim 1.6\text{--}2.4 \text{ MJ/m}^2/\text{day}$  clear-sky radiation in some industrial zones, confirming usable solar potential for decentralized PV systems.

**Table 1: Typical Monthly Solar Irradiance Pattern for Southwest Nigeria**

| Month | Solar Irradiation ( $\text{kWh/m}^2/\text{day}$ ) |
|-------|---------------------------------------------------|
| Jan   | 4.5 – 5.2                                         |
| Feb   | 4.8 – 5.3                                         |
| Mar   | 5.0 – 5.5 ★ (peak period begins)                  |
| Apr   | 5.0 – 5.4                                         |
| May   | 4.5 – 5.0                                         |
| Jun   | 4.0 – 4.6                                         |
| Jul   | 3.7 – 4.2                                         |
| Aug   | 3.5 – 4.0 ✕ (minimum)                             |
| Sep   | 3.8 – 4.4                                         |
| Oct   | 4.2 – 4.8                                         |
| Nov   | 4.5 – 5.1                                         |
| Dec   | 4.6 – 5.2                                         |

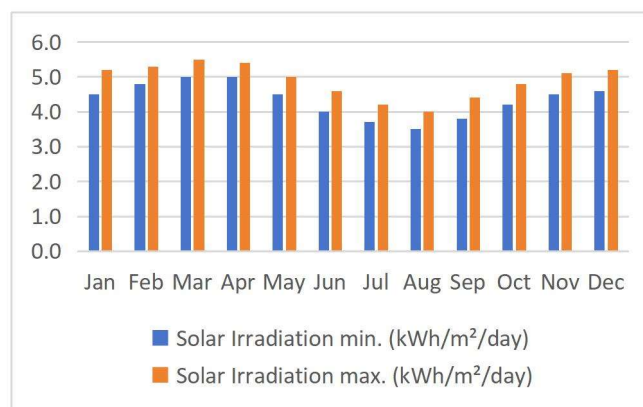


**Figure 1: Annual monthly solar irradiation in the South-West**

## 2.2 Wind Availability Data

Regarding the wind system, several studies have revealed the Southern Nigeria endowment. Several studies report that *average wind speeds in parts of southern Nigeria is in the range of about 3–4 m/s*. A study of six locations in the South-South geopolitical zone of Nigeria found annual mean wind speeds at 10 m height of about 3.3 to 3.7 m/s for sites including Asaba, Benin, Port Harcourt, Uyo and others. The details in Table 2 are available in literature (Oyedepo et al., 2012, Eboibi et al., 2024):

**Table 2: Reported wind data for southern Nigeria**

| Region / Study                                        | Reported wind speed (annual mean at ~10 m), m/s | Source                    |
|-------------------------------------------------------|-------------------------------------------------|---------------------------|
| South-South (Asaba, Benin, Port Harcourt, Uyo, Warri) | 3.3–3.7                                         | Eboibi et al., 2024       |
| South-South (Calabar)                                 | ~4.4                                            | Eboibi et al., 2024       |
| South-East (Owerri, Onitsha)                          | ~3.36–5.4                                       | Oyedepo et al., 2012      |
| South-West (Ibadan, Abeokuta, Akure, Ikeja)           | ~2–7.3                                          | Nze-Esiaga & Okogbue 2014 |

Regardless of location, Nigeria energy scenario can benefit from an optimal renewable energy design. Several studies have supported the idea. Diemuodeke et al., (2016) in their discussed the feasibility, environmental benefits, reliability, and cost-effectiveness of hybrid diesel-PV-wind energy systems for underserved coastal communities in Nigeria. Kuhe et al.' (2025) showed how hybrid renewable systems can improve energy security, reduce costs, and promote long-term sustainability in Nigerian institutions. Hybrid solar-biomass systems as cost-effective, environmentally friendly solutions for expanding reliable energy access in rural Nigerian communities were identified in the work of Ifeanyi-Nze & Okayim, (2022). Strategies for using hybrid systems to reliably power rural healthcare centres and to improve energy access and system reliability were presented by Olatomiwa et al., (2023). Details of how hybrid systems combining solar, wind, and other renewables can provide efficient and cost-effective electricity to supplement Nigeria's inadequate grid were exemplified by Kamil et al., (2021). In the work of Okokpujie et al., (2025), a hybrid system comprising solar and wind was modeled and shown to improve reliability, sustainability, and energy availability in areas with weak grid connectivity.

Studies conducted across major South-Western cities such as Abeokuta, Akure, Ibadan, Ikeja, and Osogbo reveal spatial variability in wind resources. Nze-Esiaga and Okogbue (2014) reported most probable wind speeds ranging from 3.82 m/s to 7.03 m/s, with coastal and urban locations such as Ikeja exhibiting higher values.

However, as reported by Fadare (2008) and Rauff and Nymphas (2016) long-term statistical analyses suggest lower mean wind speeds in inland areas. The studies revealed that Ibadan



experiences average wind speeds typically below 3 m/s, confirming weak wind regimes inland. A broader national assessment by Kano et al. (2025) supports these findings, indicating average wind speeds of approximately 2–3 m/s across most South-Western locations.

### 2.3 Expected Current Focus in South-Western Nigeria Renewable Energy Landscape

The foregoing indicates that Southwestern Nigeria has adequate solar irradiation for sustainable PV deployment. However, the observed seasonal variability necessitates careful consideration in system design, particularly in hybrid configurations where energy reliability is critical. Additionally, the observed wind speed range of approximately 2–4 m/s across much of southern Nigeria is generally below the optimal threshold for large-scale wind power generation. Most commercial wind turbines require higher wind speeds for efficient operation. However, these conditions are suitable for specially designed small-scale wind turbines, distributed energy systems, and hybrid renewable energy systems (e.g., wind-solar-diesel or wind-solar-battery systems).

Hybrid systems are particularly advantageous in this context because they present the following advantages:

- i. Compensate for the intermittency of wind resources
- ii. Improve system reliability
- iii. Reduce dependence on fossil fuels
- iv. Optimize overall energy generation costs

The literature consistently demonstrates that southern Nigeria exhibits low to moderate wind energy potential, with average wind speeds typically ranging from 2 m/s to 4 m/s. While this limits the feasibility of large-scale standalone wind power systems, it strongly supports the adoption of solar hybrid renewable energy systems for sustainable and reliable power generation in the region. This study proposes a solar-wind hybrid renewable energy system for every zone in the country.

Solar PV Renewable energy technologies continue to gain attention due to abundant solar resources. Conventional wind turbines require higher wind speeds ( $\geq 5$  m/s) for efficient operation, making them unsuitable for regions like Ilaro. However, recent advances in low cut-in speed turbines (2–3 m/s) present new opportunities.

Some of the recent advanced low cut-in wind speed turbines and their characteristics are as follows:

- i. Tumo-Int (China)
  - Models: 10 kW – 50 kW;

- Cut-in speed: 2.5-3.0 m/s
- Designed for small/medium hybrid systems
- Often paired with solar + battery systems
- Good performance at low–moderate wind
- Can be deployed as Tumon-Int 15 kW / 20 kW models

ii. KenGen (Kenya) – *low-wind turbines*

- Cut-in speed: 3.0-4.0 m/s
- Turbines built for East African wind profiles
- Has smaller turbines with low cut-in
- Good field service in West & East Africa
- Example: KenGen 15 kW low-wind

iii. Bornay (Spain) – *small & medium turbines*

- Models: 5 kW – 30 kW
- Cut-in speed: 3.0 m/s
- Known for reliability
- Good customer support networks
- Example Bornay 24 kW for hybrid systems

iv. Xantrex / Windy Nation / Bergey (US);

Other brand used globally in small wind + solar hybrids.

- Bergey Excel 15 kW — relatively low cut-in
- Cut-in speed: 3.0 m/s
- Windy Nation 10 kW
- Southwest Wind Power Skystream — small, mainly residential



These wind turbines can work well for southwestern Nigeria.

In this study, a solar-wind hybrid system capable of supplying energy continuously at a low cost is proposed for deployment in Ilaro, South-West Nigeria. The proposed system energy should provide reliability and economic performance in low-wind environments. Solar and wind renewable technologies deployment are capital-intensive.

Although several studies have investigated hybrid renewable systems in Nigeria, limited attention has been given to the techno-economic feasibility of integrating low cut-in wind turbines into PV systems under extremely low wind regimes typical of inland South-West Nigeria. In these studies, the optimal design of a PV-wind hybrid system has not been well studied vis-a-vis low wind regions of the country such as the South-West. Thus, it is aimed in this study to provide a techno-economic analysis of deploying a small solar-wind hybrid system. This study investigates whether integrating such turbines with PV systems can enhance energy reliability and economic performance in low-wind environments.

### **3. Methodology**

#### **3.1 Simulation Approach**

A techno-economic simulation framework was developed to evaluate system performance. Three system configurations were analyzed:

- PV-only system
- Wind-only system
- PV–Wind hybrid system with battery storage

The simulation approach helps in analyzing the best renewable deployment for a medium solar irradiance and low wind environment, such as Ilaro. The following evaluation metrics are considered:

- Net Present Cost (NPC)
- Cost of Energy (COE)
- Reliability (Unmet Load %).

#### **3.2 Input Data**

The critical solar and wind parameters of interest are as in Table 3.:



**Table 3: Solar-wind parameters for simulation**

| Parameter               | Value                       |
|-------------------------|-----------------------------|
| Average Solar Radiation | 5.0 kWh/m <sup>2</sup> /day |
| Clearness Index         | 0.52                        |
| Wind speed at 10 m      | 2.5 m/s                     |
| Wind speed at 30 m      | 3.2 m/s                     |
| Wind speed at 50 m      | 3.8 m/s                     |

Wind speeds at hub height were estimated using the power law:

$$V = V_0 \left( \frac{H}{H_0} \right)^\alpha \quad (1)$$

where:

V = wind speed at height H

V<sub>0</sub> = reference wind speed

α = surface roughness coefficient (~0.14)

For the simulation, a small load profile of 250 kWh/day was considered with a peak load of 15 kW and a night load slightly more than half at 8 kW. For the load profile of 15 kW. PV array of 20 kW, a wind turbine of 5kW, battery storage of 100 kWh, and an inverter with 95% efficiency were selected.

### 3.3 Levelized Cost of Energy (LCOE)

As renewable energy systems are usually capital-intensive, there is a need to carry out a levelized cost assessment of the system. To determine the economic viability of the proposed hybrid system, a Levelized Cost of Energy (LCOE) is evaluated. It provides a comprehensive measure of the cost per unit of electricity generated over the system's lifetime, enabling direct comparison with alternative energy solutions and justifying the adoption of hybrid renewable systems in low wind regions. This assessment includes initial capital, maintenance, replacement (batteries, inverter), and cost over the system's lifetime. A sensitivity analysis of the system was also carried out. The LCOE is given as

$$\text{LCOE} = \frac{\text{Total Lifetime Cost}}{\text{Total Energy Produced}} \quad (2)$$

The net present cost is determined as:

$$\text{NPC} = \sum_{t=0}^N \frac{C_t}{(1+r)^t} \quad (3)$$

where: C<sub>t</sub> = cost at year t

r = discount rate

N = project lifetime.

The reliability of the system is determined from:

$$\text{LPSP} = \frac{\sum \text{Energy Deficit}}{\sum \text{Total load demand}} \quad (4)$$

## 4. Results and Discussion

### 4.1 Energy Production



The results of the energy simulation for the three scenarios are presented in Figure 2. The PV only system produced 32,500 kWh, wind only a paltry 8,200 kWh while the hybrid system produces 39,800 kWh of energy. An annual energy requirement of 250kWh was intended. In determining the economic viability of the system, the simulated results in Table 4 show that the hybrid system is more economically viable than the other energy sources. The results in Figure 3 show the reliability of each of the three scenarios by giving the percentage of the unmet load. The impact of the wind speed on energy production in the area was presented in the sensitivity analysis results in Table 5, while the effects of solar irradiation are seen in Table 6.

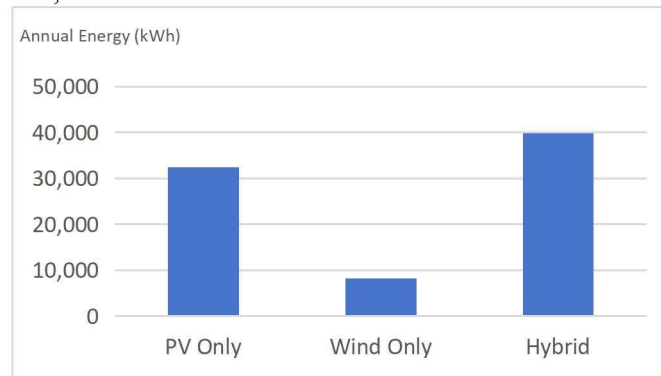


Figure 2: Annual energy generation from all systems

Table 4: Economic viability results

| System    | NPC (\$) | COE (N/kWh) |
|-----------|----------|-------------|
| PV Only   | 36.44m   | 261         |
| Wind Only | 56.66m   | 495         |
| Hybrid    | 38.92m   | 202         |

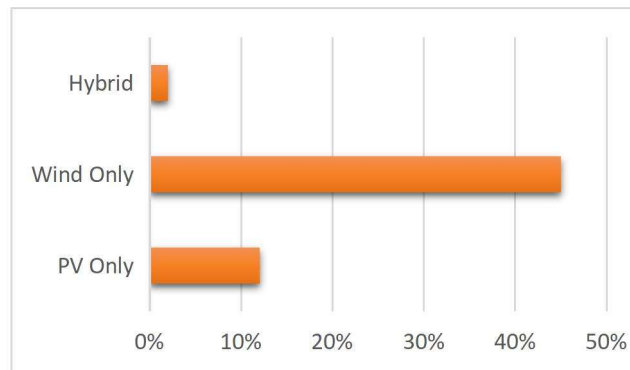


Figure 3: Reliability results (unmet load)

Table 5: Wind impact analysis results

| Wind Speed (m/s) | COE (N/kWh) |
|------------------|-------------|
| 2.5              | 248         |
| 3.5              | 206         |
| 4.5              | 179         |



**Table 6: Solar Impact analysis**

| <b>Solar Radiation (kWh/m<sup>2</sup>/day)</b> | <b>COE (\$/kWh)</b> |
|------------------------------------------------|---------------------|
| 4.0                                            | 0.17                |
| 5.0                                            | 0.15                |
| 6.0                                            | 0.13                |

#### **4.2 Discussion**

The results show that wind energy alone is not viable in Ilaro due to low wind speeds. The wind-only system exhibits high cost and poor reliability. The PV-only system performs better, but due to its day/night intermittency, it requires significant battery storage.

The best performance is the hybrid PV–wind system as it leverages the complementary nature of solar and wind resources. The contribution of wind energy during nighttime and cloudy periods reduces battery dependency and improves system stability. It is to be noted that this is only achievable due to the inclusion of low cut-in wind turbines, which are critical to achieving this performance.

#### **5. Conclusion**

The hybrid systems can significantly improve energy access in rural and off-grid areas of Nigeria, where the national grid is unreliable or absent. This study shows that the hybrid system (solar-wind) can reduce operational costs and increase energy generation reliability. The additional benefit of the hybrid system is the beneficial effect on the environment. The hybrid system achieved the lowest COE and highest reliability, confirming its suitability for deployment in South-West Nigeria. To achieve an optimal performance, proper system design, including low-speed wind turbines and adequate storage, is essential.

Hybrid systems reduce greenhouse gas emissions compared to fossil fuels, contributing to energy sustainability and climate goals. This study can be extended to other geopolitical zones of the country. As seen in the wind data obtained, several other locations in Nigeria have better solar-wind performance index. Thus, applying similar methods to those employed in this design to those other locations can prove to be beneficial to the feasibility analysis for the locations. This study focused on a small electric load of 15 kW only. Further study can be carried out to determine a more elaborate design for a higher energy demand for Ilaro, which can serve as a basis for the design of a techno-economic feasibility assessment for other areas.

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