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Prospects and Challenges of Deploying Solar-Wind Hybrid Energy Systems for Off-Grid Electrification in Zimbabwe

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Abstract: Zimbabwe has a long history of electricity shortages especially in off-grid and rural regions where extension of grids is costly. Although the solar photovoltaic systems are quite common, their intermittency restricts regular power supply. The combination of wind and solar power can be more reliable due to the complementary nature of the resources. The paper evaluates these opportunities and challenges of implementing solar-wind hybrid energy systems to off-grid electrification in Zimbabwe, including the resource potential, the main strengths, and the obstacles, including the high cost, inaccessible wind data, and policy limitations.

Keywords Hybrid systems, Off-grid electrification, Renewable energy, Solar energy, Wind energy, Zimbabwe

1. Introduction

There are numerous renewable energy sources in Zimbabwe including solar, wind, biomass, and hydropower, which can greatly enhance the current electricity related issues in the country(Makonese, 2016). Even after such theoretical richness, Zimbabwe has witnessed sustained power shortages instigated by old-generation infrastructure, climate-related changes in hydropower production and failure to invest in new generation capacity. As of 2022, the total installed generation capacity of electricity in the country is about 2,531 MW. The effective available capacity, however, is significantly smaller with a typical production of 1,300 MW-1,500 MW because of inefficiency in operations, ageing infrastructure, and hydrological limitations. This is less than the national electricity demand, estimated at approximately 1,600 MW, which causes a long-term shortage in the electricity supply(Country Guide: Zimbabwe, 2023). As a result, there is often long-term load-shedding in the country, and in some situations the outages go up to 18 hours a day (Brandt et al., 2022). In the future, the demand for electricity is expected to rise as well to around 5,177 MW in 2030, which adds more pressure on the current supply demand disparity as noted by the world bank (world bank, 2023).

The consequences of Zimbabwe electricity shortage go far beyond house inconvenience, and this is a major limitation to economic growth, social development, and industrial productivity(Moreblessing et al., 2024)Rapid urbanization, population growth, and increased housing development further exacerbate demand pressures. However, with increasing demands, Zimbabwe continues to be highly reliant on imports of electricity supplied by regional power companies in South Africa, Mozambique, and Zambia(Brandt et al., 2022). Hydropower, which traditionally forms the main part of the national energy structure, has become less reliable. With a capacity of 1,050 MW, the Kariba South Hydropower Station has in the recent years been running at severely reduced levels as low as 180 MW owing to frequent droughts, diminishing inflows to the reservoir, and climate variability related to climate change(Country Guide: Zimbabwe, 2023).These dynamics show the increased demand to diversify the energy mix in Zimbabwe to more climate-resilient and decentralized energy.

2. Background

Decentralized renewable energy systems, especially solar photovoltaic (PV) technologies have been widely used in both urban and rural areas in response to the continued grid unreliability(Mulugetta et al., 2000).
Solar irradiation in Zimbabwe is 5.7 kWh/m 2/day on average and solar energy is one of the most readily available and economically feasible renewable resources in the country(Chahuruva & Dei, 2017).The National Energy Compact of Zimbabwe states that the major renewable energy objective of the country is to achieve a higher renewable potential of 2,640 MW by 2030 (as compared to 1,282 MW in 2024) that will generate 48.6% percent of the total expected generation(Ministry of Public Service Labour and Social Welfare, 2023).As a result, households, small enterprises, and facilities are now turning to rooftop PV systems as an addition to the grid supply during outages. However, the inherent intermittency of solar energy, particularly during cloudy conditions and nighttime periods, limits its ability to provide reliable, continuous power when deployed as a standalone solution(Asare-Addo, 2026). This constraint explains why hybrid energy systems that combine complementary renewable resources to increase supply reliability, and the overall performance of the system are required.
Wind energy has not been highly exploited as compared to solar in Zimbabwe, but it is also quite promising in hybridization. The country's diverse topography gives rise to localized zones of moderate wind resources, particularly in the Eastern Highlands, Mashonaland Central Province (Mt Darwin and Guruve), Midlands Province (Vungu and Shangani) and Matabeleland South Province (Bulilima and Mangwe) (Sas, 2025). Global Wind Atlas data show wind speeds more than 6m/s at 100m height at various locations in the above indicated areas, which are suitable for small- to medium-scale wind power applications. The cut-in speed of wind turbines is typically between 7 and 10 mph (about 3 to 4.4 m/s). Figure 1 illustrates the wind turbine power curve based on Vestas Horizontal turbines.
Importantly, many of these regions also receive high solar irradiation, creating favorable conditions for solar–wind resource complementarity. The winds tend to move faster during times of low solar energy like during cloudy days or during the evening hours. Solar-wind hybrid solutions are bound to be beneficial to off-grid and rural communities, most of which are not connected to the national grid because of economic limitations and geographical isolation. A solar–wind hybrid energy system is an integrated power generation system that combines solar photovoltaic (PV) panels and wind turbines to generate electricity from both solar radiation and wind resources. The hybrid systems use two complementary renewable energy sources to decrease the reliance of either source or increase the reliability of the system as a whole (Seiyefa Aondo Vincent et al., 2024). The common set up of a hybrid solar-wind system is shown in Figure 2.
The hybrid renewable energy systems are modular, scalable and have a higher degree of resilience, which is why they can be a good fit for rural electrification, community infrastructure, etc. Nevertheless, the literature on solar-wind hybrid energy systems in Zimbabwe is still scarce and scattered.

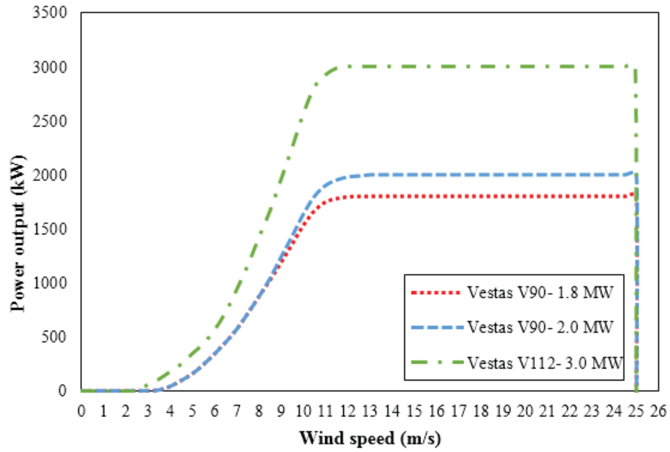

Figure 1 Power output curve of a Vestas horizontal-axis wind turbine across different wind speeds

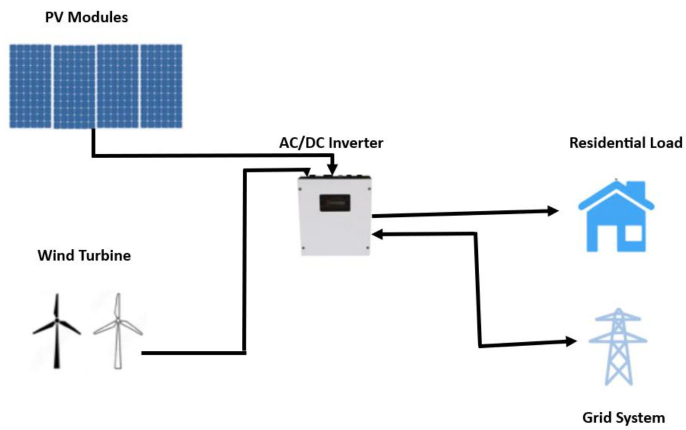

Figure 2 Typical configuration of a solar–wind hybrid energy system integrating photovoltaic panels and wind turbines

3. Materials and methods

Relevant data were collected from a wide range of sources, including peer-reviewed journal articles, government publications and technical reports. Scientific sources were taken through recognized scientific databases like the IEEE Xplore and Google Scholar databases.

Policy and institutional information were obtained from official publications by the Zimbabwe Electricity Transmission and Distribution Company (ZETDC), the Ministry of Energy and Power Development, and the Zimbabwe Energy Regulatory Authority.

For solar energy, the literature consistently highlights Zimbabwe's advantageous position within a high-insolation belt, receiving on average 5.7 kWh/m²/day of solar radiation and approximately 4000 hours of sunshine annually (Chiteka et al., 2024). For wind energy, data were drawn from significant studies such as Hove, Madiye and Musademba, who analyzed wind speed distributions using Weibull parameters and identified Gweru as having the highest recorded power density of 115 W/m² at a 50 m hub height (Hove et al., 2014). Other reports on national monitoring of wind resources in Chimanimani, Chivhu, Karoi, Mt Darwin, and Rusape reported that approximately 33% of Zimbabwe has wind resources that could be utilized to generate power on small scale although the wind power density of a nation is generally low (Samu et al., 2019a).

3.1 Solar wind hybrid projects in Zimbabwe

The literature has also analyzed the historical and current examples of the use of wind and solar. Previous history records that water was pumped by windmills, and the activities of ZERO, a local NGO, which produced 1 kW and 4 kW wind turbine prototypes in the late 1990s following the successful feasibility studies. The same projects, in addition to five previous turbine installations in Rusape, helped set the groundwork in the wind energy discussion in the country (Samu et al., 2019b). More recent developments, e.g., the design of a 160 W solar wind hybrid streetlight in Gweru in 2019 in Figure 3 below, showed the increasing technical maturity of hybrid systems. The reliability rate of that design was 98.4%, and the performance was enhanced significantly with the introduction of a diffuser, which has increased turbine output and reduced required solar and battery capacity (Nyemba et al., 2019).

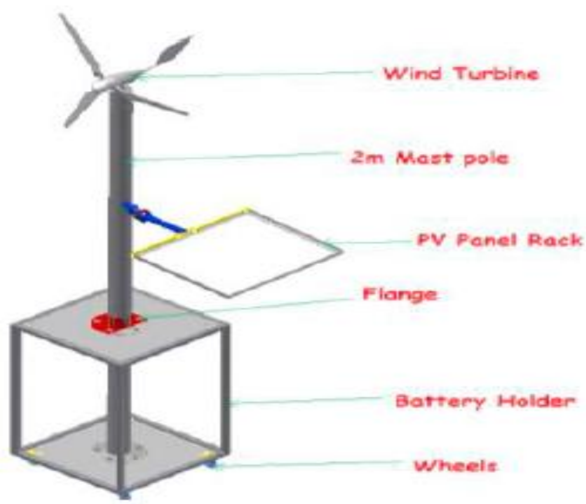

Figure 3 Design model of a 160 W solar–wind hybrid streetlight system(Nyemba et al., 2019)

Another indication of the performance and economic feasibility of the solar–wind hybrid systems in Zimbabwe is the feasibility study of a grid-connected hybrid PV power plant of wind power in the Gwanda District by Samu and colleagues as shown in Figure 4 below. A hybrid design was assessed in the study and was based on a Vestas V90 -1.8 MW wind turbine prototype paired with a 1000-kW solar photovoltaic array(Samu et al., 2019). The optimal configuration of the system identified based on techno-economic optimization was a single 1.8 MW wind turbine coupled with the PV plant, with the minimum levelized cost of electricity (LCOE) of 0.21 USD/kWh, a renewable energy system (RES) of 42%, and a capacity factor of 0.16.

Although the hybrid plant was found to be technically feasible and having a high renewable penetration level, the study found that the LCOE of the proposed hybrid system was still higher than the current average cost of electricity generation in Zimbabwe, which is estimated at around 0.10 USD/kWh. This gap can be explained in large part by the fact that the country still depends on the old hydropower infrastructure and cheaply fueled coal-generated power plants which enjoy the advantages of amortization of historical capital and fuel subsidies. The feasibility of solar-wind hybrid energy systems in Zimbabwe was also tested in practice with the Murehwa Test Run Project being a pilot project of a wind-solar hybrid system designed to provide power to a five-roomed home with a household of four people. It used a 200 W wind turbine and a 100 W solar photovoltaic panel installed(Dahwa, 2017). Before the hybrid system was introduced, the household was powered by a 100 W solar panel that was independent and attached to a 100 Ah battery. In this arrangement, there was limited power supply, and the family could only use their entertainment system to full capacity for a maximum of 3 hours after which they had to turn off most of the appliances to reserve the remaining battery charge to light up the important items.

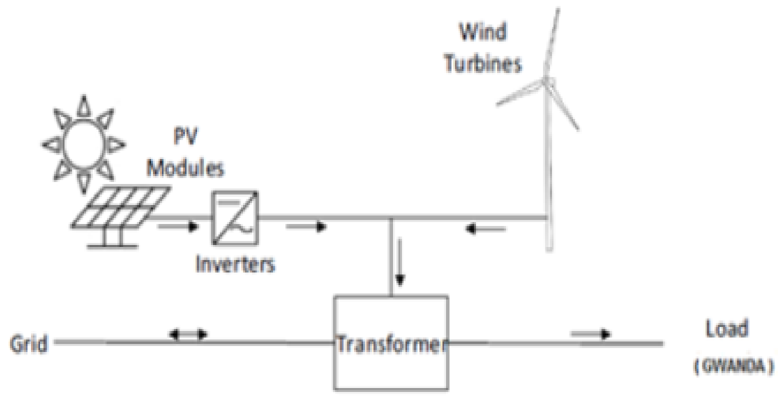

Figure 4 Schematic of a grid-connected solar–wind hybrid power plant modeled for Gwanda(Dahwa, 2017)

With the wind turbine injected into the system it was noted that there was a significant increase in energy availability and reliability. The hybrid set up allowed the home to utilize electricity around 24 hours a day without the necessity to ration the electrical appliances. The supplementary role of wind energy especially at evening and night times when there was no solar generation minimized the amount of battery discharge.As a result,the battery state of charge was always kept at an above 50% depth of discharge (DoD) level, a level which is known to significantly extend battery life and increase the overall system life.However, while the project showed the technical possibilities and reliability advantages of solar-wind hybrid systems in rural electrification, small scale and location-specific nature restricts the generalizability of findings..Additionally, the absence of long-term performance monitoring, detailed wind resource measurements, and economic cost–benefit analysis highlights the need for more comprehensive, data-driven pilot projects to support large-scale deployment and policy formulation.

Zimbabwe Government, through the Ministry of Energy and Power Development (MoEPD) is undertaking a national Wind Resource Assessment presently in consideration of the development of Wind Power Plants. Based on Global Wind Atlas Satellite data, the selected sites for Met Masts installations show promising wind speeds sufficient for commercial wind power production as given in Table 1 below. Coincidentally, there is vast land and high solar irradiance in the vicinity of these sites, thus presenting a strong case for sustainable Solar-Wind Hybrid Energy systems.

Table 1 Wind resource assessment sites based on Global Wind Atlas data

Site	Coordinates	Mean Wind Speed at 100m(m/s)
Dotito	-16.500287°, 31.544878°	7.45
Chishwiti	-16.31981°, 31.680151°	6.96
Vungu	-19.650024°, 29.466749°	7.02
Bulilima	-20.401594°, 27.890554°	6.55
Guruve, Dave Farm	-16.511808°, 30.654989°	6.51
Guruve, Nyamuti	-16.648692°, 30.813604°	7.43

To put the potential Solar-Wind complementarity into perspective in respect of the wind data provided above, we assessed the Solar potential for Guruve Nyamuti site (-16.648692°, 30.813604°) using Photovoltaic Geographical Information System (PVGIS) Typical Meteorological Data. Figure 5 depicts

2023 monthly solar irradiation estimates from PVGIS at Guruve Nyamuti Wind Site. The data shows Global Horizontal Irradiation (GHI) for the year fluctuating from 149.18kWh/m2/month (~5 Peak Sun Hours) to a maximum of 212.39kWh/m2/month (~7 Peak Sun Hours). At an optimum module angle, deduced from iterations to be 22.9°, the potential solar yield is quite high reach a maximum of 223.21kWh/m2/month. The estimated GHI for this site is way above thresholds for Solar PV investment viability which coincidentally exist with a sustainably high estimate mean wind speed of 7.43m/s. Any Solar-Wind Hybrid system is poised for success with such conditions.

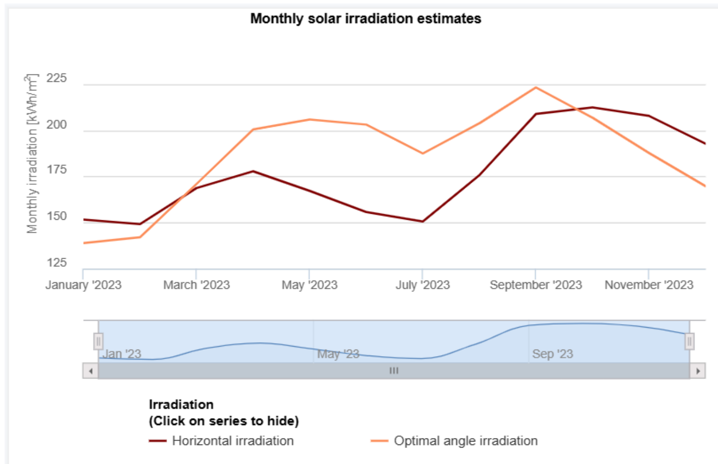

Figure 5 Monthly solar irradiation (GHI) estimates for Guruve Nyamuti site based on PVGIS data (https://re.jrc.ec.europa.eu/)

4. Methodology

The meteorological data used in this study was retrieved from PVGIS, a widely used and reliable online tool for solar resource assessment and renewable energy system performance evaluation. The data was downloaded and saved in MS-Excel format which included hourly meteorological parameters necessary to evaluate the solar photovoltaic (PV) energy potential, PV system performance and wind energy potential at the selected study site. The selected site was Dave Farm in the rural area of Guruve in Zimbabwe, where access to grid electricity remains a significant challenge. The site was selected due to its potential for decentralized hybrid renewable energy applications aimed at improving rural electrification. Hourly meteorological data for a selected 24-hour period, presented in Table 2 below, were extracted from PVGIS for Guruve, Dave Farm located at coordinates -16.511808°, 30. 654989°.The wind speed data was referenced at a height of 10 m above ground level.

4.1 Calculating Rb

To capture the maximum amount of solar energy, solar collectors and photovoltaic panels are usually tilted. To accurately assess energy availability, beam radiation on a tilted surface must be derived from the beam radiation on a horizontal surface(Duffie & Beckman, 2013) . This is accomplished using the geometric factor Rb which is the ratio of the radiation received by the tilted plane to the radiation received by a horizontal plane at one particular time. Thus,

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (1)$$

where, R_b is beam radiation tilt factor, θ *is* angle of incidence between the sun's rays and the normal to the tilted surface, θ_z is solar zenith angle.

Table 2 PVGIS Hourly Wind and Solar Irradiation data for Guruve Dave Farm

Date	Hour(t)	G(h)	Gb(n)	Gd(h)	Windspeed (m/s) at 10m
30/10/2023 00:59	0	0	0	0	4.97
30/10/2023 01:59	1	0	0	0	4.83
30/10/2023 02:59	2	0	0	0	4.62
30/10/2023 03:59	3	0	0	0	4.34
30/10/2023 04:59	4	122	66.59	100	3.86
30/10/2023 05:59	5	324	203.24	213	5.03
30/10/2023 06:59	6	365	62.84	319	5.72
30/10/2023 07:59	7	660	306.16	392	7.17
30/10/2023 08:59	8	670	188.33	488	6.48
30/10/2023 09:59	9	974	646.75	328	6.14
30/10/2023 10:59	10	1000	736.69	285	5.79
30/10/2023 11:59	11	991	940.61	160	5.38
30/10/2023 12:59	12	593	247.48	409	5.17
30/10/2023 13:59	13	326	51.77	297	5.17
30/10/2023 14:59	14	362	563.57	167	5.24
30/10/2023 15:59	15	115	216.28	90	5.1
30/10/2023 16:59	16	0	0	0	4.28
30/10/2023 17:59	17	0	0	0	4.62
30/10/2023 18:59	18	0	0	0	5.38
30/10/2023 19:59	19	0	0	0	5.03
30/10/2023 20:59	20	0	0	0	5.1
30/10/2023 21:59	21	0	0	0	4.76
30/10/2023 22:59	22	0	0	0	4.69
30/10/2023 23:59	23	0	0	0	4.62

4.2 Calculating solar radiation incident on a tilted surface (Gt)

Once the geometric factor Rb was obtained, all the other factors needed for calculating the total solar radiation received on an inclined plane (Gt) were defined for application of the Collares-Pereira and Rabl Sky Model. The model was chosen because of its simplicity and the ease of calculation of the solar radiation received by an inclined surface. The Liu and Jordan model gave a more realistic approach but was further simplified by Collares-Pereira and Rabl (1979) who assumed that the brightness of the sky equals the brightness of the ground(Duffie & Beckman, 2013). It was this assumption that allowed for a simpler expression used for estimating solar radiation on a tilted surface which is expressed as:

$$G_T = (G_h - G_d)R_b + G_d \quad (2)$$

where, Gt is the total solar radiation on the tilted surface, G(h) is global horizontal radiation, Gd(h) is the diffuse horizontal radiation, Rb accounts for the direct radiation component.

4.3 Calculating Cell Temperature (T_c)

The adopted model for estimating PV cell temperature is the Hove Cell Temperature Model (Hove, 2000), which was chosen for being practical, empirically reliable and appropriate for real world operating conditions. The Hove Cell Temperature Model is expressed as:

$$T_c = T_a + 0.9G_T\left(\frac{T_{c,NOCT}-T_{a,NOCT}}{G_{T,NOCT}}\right) \quad (3)$$

Where:

- T_c= photovoltaic cell temperature $(°C)$
- T_a= ambient temperature $(°C)$
- G_T= solar irradiance incident on the PV module surface (W/m^2)
- $T_{c,NOCT}$= cell temperature under Nominal Operating Cell Temperature (NOCT) conditions $(°C)$
- $T_{a,NOCT}$= ambient temperature under NOCT conditions $(°C)$
- $G_{T,NOCT}$= solar irradiance under NOCT conditions, typically $800\ W/m^2$

4.4 Calculating Photovoltaic Field Efficiency (η_{PV})

The photovoltaic (PV) field efficiency represents the ability of the PV system to convert incident solar radiation into usable electrical energy under operating conditions (Duffie & Beckman, 2013)
The PV field efficiency was calculated using the equation:

$$\eta_{PV} = \eta_{STC}\left[1-\beta\left(T_c-T_{c,STC}\right)\right] \quad (4)$$

where,

- η_{PV}= photovoltaic field efficiency
- η_{STC}= reference efficiency of the PV module under standard test conditions
- β= temperature coefficient of the PV module $(°C^{-1})$
- T_c= PV cell temperature $(°C)$
- T_{cSTC}= reference temperature, at standard test conditions $25°C$

4.5 Calculating Photovoltaic Power Output (P_{PV})

The PV power output was calculated using the formular:

$$P_{PV} = P_{STC}\left(\frac{G_T}{G_{STC}}\right)\left(\frac{\eta_{PV}}{\eta_{STC}}\right) \quad (5)$$

where,

- P_{PV} = Instantaneous power output of the PV generator (W)
- ηPV = PV efficiency under real operating conditions, dependent on cell temperature
- η_{STC} = PV module efficiency at Standard Test Conditions (STC)
- GT = Incident solar irradiance on the PV module (W/m^2)
- G_{STC} = Standard Test Condition irradiance (1000 W/m^2 at 25°C cell temperature)
- P_{STC} = Rated power output of the PV module/array at STC

4.6 Calculation of Wind Speed at 100 m hub height

The wind speed at the study site was further validated using hourly wind data obtained from PVGIS. The PVGIS dataset provides wind speed measurements at a reference height of 10 m above ground level. To estimate the wind speed at the selected turbine hub height of 100 m, the wind speed values were extrapolated using the one-seventh power law, as shown below.

$$V_{100m} = V_{10m}\left[\frac{H\_100m}{H\_10m}\right]^{\frac{1}{7}} \quad (6)$$

where,

- V_{10m}= wind speed at reference height of 10m
- V_{100m}= estimated wind speed at hub height of 100m
- H_{10m}= reference height (10 m)

- H_{100m}= hub height (100 m)

These extrapolated wind speeds at 100 m hub height were then computed and presented below in the column of wind speed at 100m

4.7 Maximum Power Output of the wind turbine

According to the aerodynamic principles of energy conversion, the maximum power a wind turbine can produce from wind is bounded by the Betz limit theory. The kinetic energy of wind is created by the motion of air masses, and a wind turbine transforms some of the kinetic energy into mechanical energy, which is then converted to electrical energy with a generator. The theoretical maximum power that can be generated by a wind turbine is given as:

$$P_{TMAX} = \frac{1}{2}\,\rho_a\,A_T V^3 \frac{16}{27} \quad (7)$$

where,

- P_{TMAX}= Maximum power output of the wind turbine (W)
- ρ_a= Air density (kg/m^3)
- A_T= Swept area of the turbine rotor (m^2)
- V= Wind velocity (m/s)
- $\frac{16}{27}$= Betz limit coefficient

Assumed Parameters:

i. Solar System size – 3000Wac
ii. Standard atmospheric conditions were assumed for the air density. The air density was taken as: ρ_a= 1.225 (kg/m^3)

This value corresponds to dry air at sea level under standard atmospheric conditions. The swept area of the wind turbine rotor was assumed to be $A_T = 10\ m^2$.

This assumption is a small-scale wind turbine of horizontal axis type which can be used for decentralized and rural applications in energy generation. Swept area is the circular area swept out by the rotating blades and directly affects the amount of wind energy that is caught by the turbine. The governing wind power equations were used to calculate the wind turbine power output, based on the above stated assumptions and operating parameters. The values that result from the analysis are shown in Table 3.

After the calculations were completed, a graph was plotted using Microsoft Excel to illustrate the variation of wind turbine power output and photovoltaic (PV) power output over the selected 24-hour period for the study site at Dave Farm, Guruve. The graph was used to demonstrate the complementarity between wind and solar energy resources at the selected location. The resulting plot is presented in Figure 6.

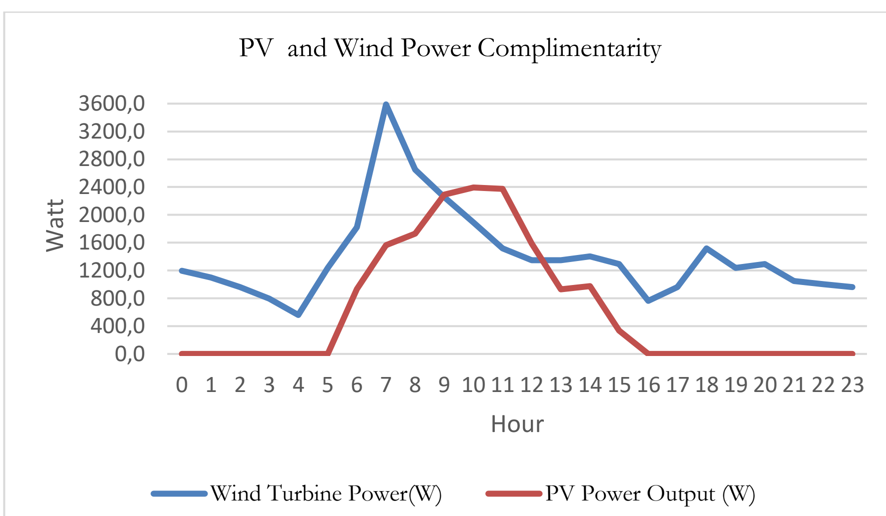

Figure 6 .24-hour variation of wind and PV power output at Dave Farm, Guruve showing resource complementarity.

Table 3 PVGIS Wind and Solar Irradiation data for Guruve, Dave Farm

Hour	Rb	It (Gt)	Tc	ηPV	Ppv	Wind speed at 100m(m/s)	P_{TMAX} Wind Turbine Power Output(W)
0	0	0	17.06	0	0	6.91	1195.4
1	0	0	17.08	0	0	6.71	1097.2
2	0	0	17.19	0	0	6.42	960.2
3	0	0	17.27	0	0	6.03	796.0
4	0	100	20.8175	0	0	5.36	560.0
5	0	213	25.409875	0	0	6.99	1239.2
6	0	319	29.509625	0.205264894	935.4214444	7.95	1822.3
7	0.632088114	561.399614	38.4225133	0.195906361	1571.167937	9.96	3589.1
8	0.792411437	632.218881	42.0936485	0.192051669	1734.552734	9.00	2649.5
9	0.854756	880.172376	51.1952359	0.182495002	2294.672282	8.53	2253.9
10	0.884694762	917.556755	50.8007864	0.182909174	2397.564976	8.05	1890.0
11	0.898996988	907.066497	50.3921448	0.183338248	2375.714033	7.48	1516.3
12	0.903287586	575.204916	40.7618493	0.193450058	1589.620349	7.18	1345.6
13	0.898996988	323.070913	33.083279	0.201512557	930.0406532	7.18	1345.6
14	0.884694762	339.515479	33.0927827	0.201502578	977.3320609	7.28	1401.0
15	0.854756	111.3689	25.4728303	0.209503528	333.3168211	7.09	1291.6
16	0.792411437	0	21.17	0.2140215	0	5.95	763.4
17	0.632088114	0	20.18	0.215061	0	6.42	960.2
18	0	0	19.1	0.216195	0	7.48	1516.3
19	0	0	18.58	0	0	6.99	1239.2
20	0	0	17.72	0	0	7.09	1291.6
21	0	0	17.66	0	0	6.61	1050.2
22	0	0	17.53	0	0	6.52	1004.5
23	0	0	17.47	0	0	6.42	960.2

The above analysis of the potential solar energy production and potential wind energy production at Dave Farm in Guruve indicates that there is strong complementarity between the two variable renewable energy sources. This complementarity shows that the combined utilization of solar and wind resources can enhance the reliability and stability of power supply at the site. In addition, the complementary nature of the resources means that the proportion of wind energy generated can be high during times of low or no solar irradiation, which helps reduce the storage capacity needed. For instance, between hour 0 and hour 5 and between hour 16 and hour 23, PV power output was measured as 0 W, this is because there was no solar irradiation. At these times, the wind turbine was able to produce energy, further enhancing the reliability of the solar PV system, and ensuring a continuous energy supply. This demonstrates the advantage of integrating wind and solar resources within a hybrid renewable energy system, as the variability of one resource can be compensated for by the availability of the other.

4.8 Challenges of deploying solar wind hybrid systems

4.8.1 High Initial Capital Costs

The high upfront capital cost of solar–wind hybrid systems remain a significant barrier to widespread adoption in Zimbabwe (Akpan et al., 2024).Hybrid systems demand the combination of several technologies of generation, development of power electronics, energy storage systems and management infrastructure, which increases the start-up cost requirements. These costs are usually prohibitive to off-grid communities and rural communities who have limited financial resources(Fungisai Chipango, 2021). Moreover, households, cooperatives, and small-scale developers cannot easily invest in renewable energy systems because of high interest rates and macroeconomic instability (Maramura et al., 2020).

4.8.2 Energy Storage Constraints

Solar-wind hybrid systems require energy storage as a vital element to maintain stability during the low renewable generation periods(Babaremu et al., 2022). Battery systems, however, add a lot of capital and lifecycle costs. The absence of local-based manufacturing, recycling, and standardized quality assurance systems of batteries exert more pressure on sustainability and make them more dependent on other imported technologies.

4.8.3 Policy and Regulatory Barriers

Despite the existence of renewable energy policies, Zimbabwe's regulatory framework for solar–wind hybrid systems, particularly for off-grid and mini-grid applications, remains underdeveloped. The hurdles and the complex process involved in the approval of renewable energy (RE) projects are both time consuming and expensive to the development of projects(Akpan et al., 2024). There are also accusations of favoritism and non-transparent tendering, and the process of licensing is not always simple(Nyamadzawo, 2022). The unpredictability of the policies and their inconsistent implementation also provide an unstable environment in the sphere of investment and complicate long-term planning of the domestic and international investors. The National Energy Compact of Zimbabwe also identifies weaknesses in policies and procurements as one of the obstacles to the implementation of renewable energy systems in the country. The lack of a clear renewable energy procurement framework leads to noncompetitive bidding processes negatively affecting pricing and investor confidence(Ministry of Public Service Labor and Social Welfare, n.d.).

4.8.4 Limited availability of reliable wind resource data

In comparison to solar energy, which is comparatively well-documented in the whole of Zimbabwe, wind energy information is sparse and location specific. This inability to provide long-term and high-resolution wind data makes the system design, feasibility analysis, and optimization of performance more difficult, increasing the risk of underperformance(Gunda et al., n.d.). There is need to come up with wind resource maps for the country based both on satellite data and confirmed by ground measurements through erection wind masts around the country especially those areas that show potential for wind power generation. create an accurate knowledge base of the wind resource available in Zimbabwe through measurement and analysis of wind speed data, to help the country plan for wind energy projects

4.8.5 Vandalism and Theft

Theft and vandalism of installed components of solar energy are a major problem, especially in remote and off-grid locations(Cuthbert Njenda et al., n.d.). The risk of losing critical infrastructure such as photovoltaic panels, batteries, and wiring discourages potential users and investors from adopting solar-based systems, especially where adequate security measures are lacking.

4.8.6 Social Acceptance and Community Engagement Challenges

There are also social factors which affect successful deployment of solar-wind hybrid systems (Kunskaja & Budzyński, 2026). In certain societies, the lack of knowledge on wind power equipment, issues of noise, aesthetic view, land use, and not well-defined ownership and benefit sharing model might contribute to resistance or lack of acceptance. Lack of community involvement in the planning and implementation stages can lead to systems that are not congruent with the local energy requirements and hence this decreases user satisfaction and sustainability.

5. Results and Discussion

There is a huge potential of solar-wind hybrid energy systems in Zimbabwe. Other regions such as Guruve Nyamoti, Dotito, Vungu, Bulilima, and Chiswiti have conducive solar (149–223 kWh/m²/month) and wind speeds (6.5–7.5 m/s), which can be used complementary to solar or wind sources to provide more reliable electricity. One of the opportunities is this complementarity, which can provide a constant supply of power, minimize the use of large storage facilities, and make off-grid electrification in rural and remote communities scalable. The usefulness of hybrid systems can be exemplified with pilot projects. The Murehwa home project combined a 200 W wind turbine and a 100 W solar panel, which increased the 3-hour long period of power under PV-only operation to 24 hours per day. A hybrid streetlight in Gweru of 160 W achieved a 98.4 percent reliability, and a grid connected plant in Gwanda generated almost 4,000 MWh of electricity annually at a 42 percent renewable ratio. These are illustrations of technical feasibility, the enhanced energy reliability, and economic development of rural regions and are good indicators of high prospects of wider adoption. However, there are significant challenges with deployment. Off-grid communities cannot afford high-initial capital costs, requirements to store energy as well as sophisticated control systems. The adoption is further impeded by policy and regulatory uncertainties, data scarcity on wind, theft, vandalism and social acceptance.

6. Conclusion

This study has shown that solar–wind hybrid energy systems offer a technically feasible and strategically viable route to better electrifying off-grid systems in Zimbabwe. Analysis of existing literature, pilot project experiences and resource assessment data shows that some parts of Zimbabwe have a potential for hybrid renewables deployment, including regions of moderate to high wind speeds, such as in the town of Guruve, Vungu, Dotito, Chiswiti and Bulilima, where moderate to high solar irradiation potential exists. The PVGIS and Global Wind Atlas analysis for the Guruve, for example, revealed high availability of sustained wind as well as high potential for solar energy, establishing hybrid systems to enhance the reliability of supply and minimize the requirement for large battery storage systems.

The study also confirmed that solar–wind hybrid systems can be more reliable in terms of operation than single renewable energy sources, because of the complementary generation profiles of solar and wind resources. From the literature studied, it has been seen that hybrid systems have the potential to improve energy availability, minimize depth of the discharge of batteries, and contribute to rural sustainable electrification in various pilot projects and feasibility studies conducted in the past. Hybrid renewable energy systems have these characteristics which makes them technically viable solutions to Zimbabwe's increasing electricity deficiency and insufficient access in remote areas. Despite the promising resource potential, deployment remains constrained by high initial capital costs, limited long-term wind measurement data, energy storage requirements, and regulatory and financing challenges. Addressing these barriers will require coordinated policy support, expansion of national wind resource assessment programs, investment in hybrid system optimization studies, and development of enabling financing mechanisms for decentralized renewable energy projects.

Further study is required on long term site-specific performance monitoring, techno-economic optimization of hybrid configurations under the climatic conditions in Zimbabwe and introduction of advanced energy management and storage technologies. In-depth socio-economic impact studies, together with the development of scalable mini-grid deployment models, would also contribute to evidence-based planning and faster adoption of solar–wind hybrid systems in Zimbabwe.

Declaration of Ethical Standards

As the authors of this study, we declare that he complies with all ethical standards.

Credit Authorship Contribution Statement

T. Nemerai: Conceptualization, data collection, analysis, methodology, and manuscript writing.

N. Kajengo: Literature review, methodology, manuscript review, editing, and technical guidance.

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

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Data Availability

The Data that support the findings of this study are available from the Authors upon reasonable request.

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