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Article

Techno-Economic Comparative Analysis of Renewable Energy Systems: Case Study in Zimbabwe

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Abstract: Fluctuations in fossil fuel prices significantly affect the economies of countries, especially oil-importing countries, hence these countries are thoroughly investigating the increase in the utilization of renewable energy resources as it is abundant and locally available in all the countries despite challenges. Renewable energy systems (RES) such as solar and wind systems offer suitable alternatives for fossil fuels and could ensure the energy security of countries in a feasible way. Zimbabwe is one of the African countries that import a significant portion of its energy needs which endanger the energy security of the country. Several studies in the literature discussed the feasibility of different standalone and hybrid RES either with or without energy storage systems to either maximize the technical feasibility or the economic feasibility; however, none of the studies considered maximizing both feasibilities at the same time. Therefore, we present a techno-economic comparison of standalone wind and solar photovoltaic (PV) in addition to hybrid PV/wind systems based on maximizing the RES fraction with levelized cost of electricity (LCOE) being less than or equal to the local grid tariff where Gwanda, Zimbabwe, is the case study. The methodology suggested in this study could increase the utilization of renewable energy resources feasibly and at the same time increase the energy security of the country by decreasing dependency on imported energy. The results indicate that the PV/wind hybrid system does not only have the best economic benefits represented by the net present value (NPV) and the payback period (PBP), but also the best technical performance; where the maximum feasible size of the hybrid system-2 MW wind and 1 MW PV-has RES fraction of 65.07%, LCOE of 0.1 USD/kWh, PBP of 3.94 years, internal rate of return of 14.04% and NPV of 3.06×10^6 USD. Having similar systems for different cities in Zimbabwe will decrease the energy bill significantly and contribute toward the energy security of the country.

Keywords: hybrid systems; photovoltaic; wind energy; energy economics; RES investments; Zimbabwe; Africa and energy security

1. Introduction

Environmental protection, energy resources conservation, and sustainable energy development are the core challenges that the world is facing nowadays [1] especially in hard times when crises have prevailed [2,3]. Moreover, given that the demand for electricity or rather energy is continuously

increasing, being able to meet this demand in an environmentally friendly manner is of importance. Enterprises are constantly searching for upgrades in their procedures for better use [4–6]. Moreover, the issue is taken care of by utilizing clean power [7,8], usage of waste power [9] and implementing various arrangements [10,11] where assets and condition are preserved. Henceforth, adjustments on power systems to expand force and productivity are required [12].

Zimbabwe faces a deficit in its energy production. Around 35% of the energy used in Zimbabwe is imported from the Democratic Republic of Congo (DRC), South Africa and Mozambique [13]. Renewable energy can be an environmentally friendly and sustainable solution to help curb this energy deficit in Zimbabwe. Basic knowledge of the geographical location, economic situation, as well as energy demand, is required to design and develop suitable systems. Zimbabwe lies in a sunny belt, with approximately 4000 h of solar radiation per year and 5.5 kWh/m²/day of solar radiation on average [14,15]. Renewable energy has not been harnessed on a large scale in Zimbabwe. Small-scale solar photovoltaic (PV) panels for lighting and irrigation purposes are the only uses of solar energy in Zimbabwe [13]. Small windmills still exist on some farms, in which they were once used to pump water even though a study by the ZERO Regional Environment Organization concluded that there is a potential of generating power from wind resources in Zimbabwe at a hub height of 80 m [13].

Renewable energy systems comprising individual resources and/or more hybrid power systems have been a topic of recent research worldwide [12,16–23]. The early research papers on hybrid power systems were published in the mid-1980s [24]. With the advances in research, in the early 1990s wind resources could now be harnessed on a commercial scale. The problem of intermittency, grid stability and reliability led to more expansion of literature on renewables as well as hybrid systems [25].

In literature, noteworthy efforts on feasibility studies on solar PV, wind and hybrid PV-wind power systems have been made both grid-connected or stand-alone systems [17,18,26–33]. Research on hybrid systems has been undertaken but the goals of each research project differ. For two different locations in Jordan [34,35] used MATLAB and HOMER software to model economically feasible hybrid solar PV-wind power systems. Their main goal was to determine the cost of energy (COE), the net present value (NPV) and the renewable energy source (RES) fraction.

Benlouba and Bourouis [36] studied the economic and technical feasibility of different off-grid PV-wind hybrid configurations with diesel generators for a village in Algeria. Moreover, Ashok [37] found the configuration of a PV-wind hybrid system that has the lowest cost of electricity for a village in India using a Quasi-Newtonian method. He found out that a PV/wind/diesel/micro hydro hybrid system would provide electricity for a whole day at a cost of 0.14 USD/kWh. Furthermore, Samu et al. [38] concluded that the LCOE of their hybrid PV-wind power system was greater than the grid tariff solely because they used a wind turbine prototype with high cut-in speed and the competing generation sources, coal and hydro are cheaper as well.

The first research on the analysis of the solar potential of the whole of Zimbabwe was undertaken by [13]. They concluded that solar PV generation is both economically and environmentally feasible in the whole of Zimbabwe. Further studies of solar PV resources in some parts of Africa were undertaken by [15,39–44]. In summary, solar is economically feasible in various parts of Africa. Studies on possible solar home systems to alleviate the current power challenges in Zimbabwe have been performed by Chahuruva and Dei [45]. In this study, the authors performed an experiment at Ashikaga Institute in Japan to obtain results which they believed could be transferable to Zimbabwe. Results of this study could be questionable since the geographical and weather conditions in Japan are different from those in Zimbabwe. Additionally, this analysis was performed at irradiation of 8.25 kWh/m²/day against Zimbabwe's average irradiation of 5.72 kWh/m²/day. Additionally, a study on the potential of Concentrated Solar Power (CSP) in Zimbabwe was performed and it was concluded that 71.4 GW can be generated from CSP [46]. A wind map of Africa was developed by [47] and concluded that on average Africa has an onshore wind potential at a height of 80 m through Geographic Information System (GIS) analysis. Another wind resource mapping exercise was undertaken by [48] for Kenya and the southern part of Africa. Research on the techno-economic potential of wind energy has been

carried out for a remote area of Sahel Zone in Cameroon by [49,50] did an assessment for another location in Cameroon as well and determined that the total energy produced annually could reduce carbon dioxide emissions by 1200 tons per year. Their calculated results and those of the Wind Atlas Analysis and Application Program (WAsP) were in good correlation [50].

The goals and objectives of the Zimbabwe National Renewable Energy Policy (NREP) included the installation of 1100 MW of renewables by 2025 and 2100 MW of renewables by 2030. Renewables in this context referred to grid-connected solar PV, grid-connected wind, small hydro and bagasse. The policy reported the provision of tax and sale of power to third-party incentives by the government and also reduced license fees for renewable energy projects. However, the policy does not outline any possible feed-in tariffs for renewable energy resources which might still make investments unattractive. Additionally, the policy still does not mention any development of stand-alone microgrids to electrify remote areas in which the rural electrification rate is only 13% [51]. The NREP also reports that the Zimbabwean government will introduce mechanisms for funding renewable energy systems as well as implementing a renewable energy technologies program that encourages Independent Power Producers (IPPs) to invest in renewable energy projects in Zimbabwe. Additionally, a fund is to be established by the Ministry of Energy to promote solar energy to address the electricity crisis.

All of the papers reviewed for this study did not compare the economic and technical feasibilities of wind, PV and PV-wind hybrid system at the same location in order to determine the most suitable system and the most profitable one. Moreover, none of the studies in the literature considered maximizing both the technical and economic feasibilities of different standalone and hybrid PV/wind systems in Zimbabwe at the same time. Therefore, this study aims to perform a techno-economic comparative study of an on-grid wind, PV and PV/wind hybrid system to determine the best RES configuration to be installed where Gwanda, Zimbabwe, is the case study knowing that this methodology can be used to determine the best configuration to install in any region in the world. The optimal RES configurations were found based on maximizing the RES fraction with levelized cost of electricity being less than or equal to the local grid tariff; such a constraint will ensure the maximum environmental benefits of the systems, increase the energy security of the country and at the same time ensures the economic feasibility of the alternative energy systems. Such methodology will increase the utilization of the local and abundant renewable energy resources in oil-importing countries such as Zimbabwe which would count toward significant cuts in the imported energy bill. Moreover, the proposed methodology is in accordance with the NREP goals and provides a pathway to achieve these goals in Zimbabwe.

2. Theory and Methodology

2.1. Photovoltaic (PV) Energy Model

Energy production from the PV plant is affected by the ambient conditions; where the effect of the ambient temperature on the module efficiency is the only ambient condition considered in this study. The efficiency of the PV module can be estimated using Equation (1) [52].

$$\eta_{PV} = \eta_{PV,R} \times \left[1 - \beta_R \times \left(T_a + (T_{NOC} - T_{R,NOC}) \times \frac{I_T}{I_R} - T_{R,STC} \right) \right] \quad (1)$$

where η_{PV} is the photovoltaic module efficiency, $\eta_{PV,R}$ is the module reference efficiency, β_R is the temperature coefficient ($1/^\circ\text{C}$), T_a is the ambient temperature ($^\circ\text{C}$) which was obtained for Gwanda city using Meteonorm v7.1 software which generates a typical meteorological year (TMY) [52], T_{NOC} is the nominal operating cell temperature ($^\circ\text{C}$), $T_{R,NOC}$ is the reference module temperature at nominal conditions ($^\circ\text{C}$), I_T the total irradiation on a tilted surface (Wh m^{-2}), I_R is the reference irradiation at nominal conditions (Wh m^{-2}) and $T_{R,STC}$ is the reference module temperature at standard test conditions ($^\circ\text{C}$). In this study, PV modules from Canadian Solar company (Guelph, Ontario, Canada) type CS6K-285M were used [53].

After estimating the global insolation on the photovoltaic module and, with the estimation of the PV module efficiency, the hourly energy generation from the photovoltaic plant can be found. Using the methodology in Duffie and Beckman [54], the global insolation was estimated which was not repeated in this study for brevity. The hourly energy generated, E_p , can be estimated as,

$$E_p = \eta_{PV} \times I_T \times A_m \times N_m \quad (2)$$

where A_m is the single module area [m^2] and N_m is the number of PV modules.

2.2. Wind Energy Model

The wind shear coefficient (α) can represent the factors that affect the wind speed at hub height like the speed at ground level, the hub height, the time (hour, day, season), the nature of the terrain and the ambient temperature. α can be taken as $\frac{1}{7}$ if the specific data of the site is not available [55]. At hub height, the wind speed (u_Z) can be extrapolated as,

$$u_Z = u_g \times \left(\frac{Z}{Z_g} \right)^\alpha \quad (3)$$

where u_g is the wind speed at ground level (m/s), Z is the height of the hub (m) and Z_g is the ground level height (m) at which speed is measured and it is equal 10 m. The hourly wind speeds at ground level for Gwanda city were generated using Meteonorm v7.1 software. Figure 1 shows the average hourly wind speeds at 10 m in addition to the average daily global insolation on a horizontal surface in Gwanda.

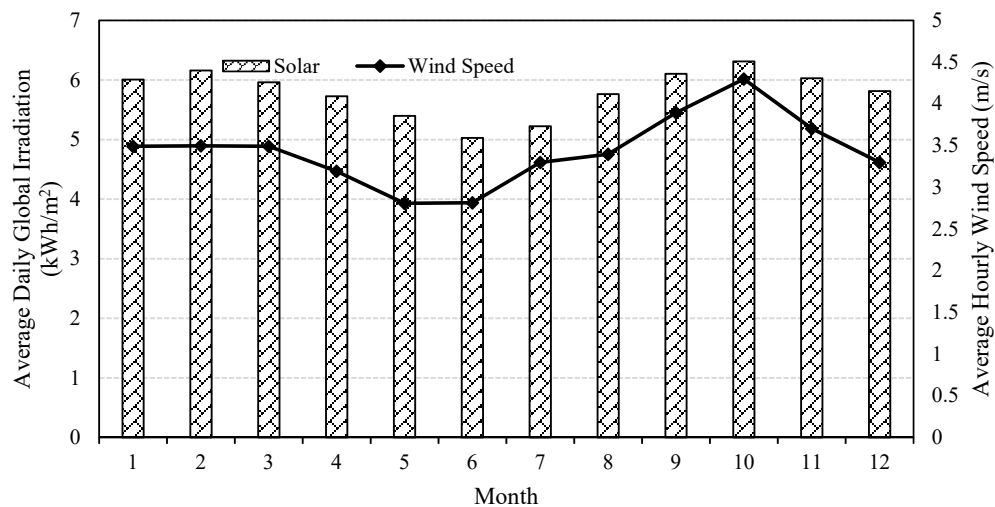


Figure 1. The average hourly wind speeds at ground level in addition to the average daily solar radiation on a horizontal surface throughout the year in Gwanda.

It is assumed that the energy generated from each wind turbine-in the case of multiple wind turbines-is the same; moreover, it is assumed that the energy production does not change during the hour. E_w which is the hourly energy production can be estimated using Equation (4).

$$E_w = \begin{cases} 0, & u_Z < u_C \text{ or } u_Z > u_F \\ N \times P_R \times \frac{(u_C)^K - (u_Z)^K}{(u_C)^K - (u_R)^K}, & u_C \leq u_Z \leq u_R \\ N \times P_R, & u_R < u_Z \leq u_F \end{cases} \quad (4)$$

where P_R is the wind turbine rated power (kW), N is the number of turbines, u_C is the wind turbine cut-in speed (m/s), u_F is the furling speed (m/s), K is the shape parameter of Weibull distribution and

it can be calculated based on Justus' theory using Equation (5) and u_R is the rated wind speed (m/s). 2 MW wind turbine (G114-2.0) from Siemens Gamesa Renewable Energy company (Vizcaya, Spain) [56] was used in this study.

$$K = (\sigma/\bar{u})^{-1.086}, 1 \leq K \leq 10. \quad (5)$$

where \bar{u} is the mean wind speed at hub level (m/s), and σ is the standard deviation of the wind speeds sample (m/s).

2.3. Performance Assessment of the RES

The harmony between the energy generation from the RESs and the demand can be inspected using the RES Fraction (F_R) which represent the percentage of demand met by the RES. F_R can be calculated as,

$$F_R = \frac{D_R}{D} \quad (6)$$

where D_R is the hourly demand met by the RES (kWh) and D is the hourly demand of Gwanda city (kWh) where the daily demand of Gwanda was obtained from [38] while the hourly load profile for Gwanda city was approximated to be like the profile of a city in Zambia [57].

Moreover, in order to inspect the autonomy of the system the demand supply fraction (DSF) which is the number of hours in which the demand is totally met by the RES in a year over the total numbers of hours in a year and it can be calculated using Equation (7).

$$DSF = \frac{H}{8760} \quad (7)$$

where DSF is the demand supply fraction (%); H is the number of hours in which the demand is totally met by the RES in a year.

2.4. The Economic Assessment of the Renewable Energy Systems (RES)

The levelized cost of electricity (LCOE) is used to assess the economic feasibility of the RESs. LCOE of the energy systems can be found using Equation (8) where the effect of the mismatching between the demand and energy production is incorporated by using the demand met by the hybrid system instead of the energy generated.

$$LCOE = \frac{C_i + \sum_{t=1}^L \frac{M_t}{(1+r)^t}}{\sum_{t=1}^L \frac{D_R}{(1+r)^t}} \quad (8)$$

where C_i is the capital cost of the RES (USD), M_t is the annual maintenance cost of the RES (USD), L is the lifetime of the system (years) where it is assumed that all the components will have the same lifetime and r is the annual discount rate. The economic parameters used in the analysis are shown in Table 1.

Table 1. The photovoltaic (PV) and wind systems economic parameters and the grid tariff in addition to the yearly discount rate for Gwanda city, Zimbabwe.

| Parameter | Value | Reference |
|---|-------|-----------|
| Photovoltaic system capital cost (USD/kW) | 1533 | [58,59] |
| Wind system capital cost (USD/kW) | 1516 | [58,59] |
| Photovoltaic maintenance cost (USD/kW) | 24.7 | [60] |
| Wind maintenance cost (USD/kW) | 39.53 | [61] |
| System expected lifetime (Years) | 25 | [59,62] |
| Grid tariff (USD/MWh) | 100 | [38] |
| Annual discount rate (%) | 7.2 | [38] |

3. Results and Discussion

Investment in renewable energy projects became attractive due to the profitability of such projects. Moreover, the deployment of RESs helps in the mitigation of greenhouse gases (GHGs) and at the same time ensures sufficient and secure energy sources. However, the significant drawback of RESs is the intermittency of the energy production from these systems due to the nature of the renewable energy resources which causes a mismatch between the demand and the supply and also affects the economics of the RESs.

The hybridization of RESs can overcome the intermittency of the resources and increase the harmony between the supply and the demand up to a certain limit where RESs can work in a synergistic way. Moreover, hybridization increases the economic benefits gained by the RESs which makes it more attractive to invest in. As the case study of this paper, Gwanda has a significant potential of wind and solar energy where the hybridization of these two resources proves that this option is the most suitable to achieve not only the maximum economic benefits but also the maximum technical benefits represented by the RES fraction, Figure 2 shows the increase in the technical feasibility of the renewable energy systems with the increase in the PV and wind capacities. However, it can be depicted from Figure 2 that after certain capacities' threshold is reached, the technical feasibility (represented by the RES fraction and the DSF) reaches saturation due to the mismatch between the demand and the supply which increase the electricity cost as shown in Figure 3. Hence, it is vital to find the optimal PV and wind capacities that achieve the maximum technical and economic benefits, Table 2 shows the economic parameters as well as technical parameters of the maximum feasible capacities of PV, wind and PV-wind hybrid systems in Gwanda.

Table 2. The maximum feasible wind, PV and PV-wind hybrid systems capacities in Gwanda, Zimbabwe, in addition to their economic and technical parameters.

| Configuration | Wind | PV | PV-Wind |
|---------------------|-------|-------|---------|
| PV Capacity (MW) | - | 1.41 | 1 |
| Wind Capacity (MW) | 2 | - | 2 |
| Capacity Factor (%) | 34.57 | 18.72 | 29.29 |
| RES Fraction (%) | 54.99 | 28.72 | 65.07 |
| DSF (%) | 32.55 | 9.57 | 42.03 |
| LCOE (USD/kWh) | 0.09 | 0.10 | 0.10 |
| NPV (million USD) | 3.00 | 0.087 | 3.06 |
| IRR (%) | 17 | 7.65 | 14.04 |
| PBP (years) | 5 | 13.1 | 3.94 |

Note that in Table 2, the hybrid system does not have the highest RES fraction and DSF only, i.e., the highest technical feasibility but also it has the highest NPV and the lowest payback period (PBP) which means that the hybrid system in Gwanda achieves the maximum economic and technical benefits compared with separate systems where solar and wind resources complement each other in a synergistic way. Moreover, note that the PV system alone has the lowest RES fraction, DSF and the lowest economic benefits since it has the lowest capacity factor among the other options due to the nature of the solar resources where on average the PV meets totally the demand of Gwanda for two hours only in a day while the wind system on average meets the demand for five hours. On the other hand, the hybrid PV/wind system meets on average the demand nine hours a day. Figure 4 shows the average hourly demand of Gwanda as well as the average hourly energy generation from the maximum feasible PV, wind and PV-wind hybrid systems.

Note that in Figure 4, the hybridization between solar and wind systems achieves synergistic performance that increases the fraction of demand met by the RES and increases the autonomy of the RES system. Figure 5 shows the monthly RES fraction and demand supply fraction of the maximum feasible PV, wind and PV-wind systems in Gwanda.

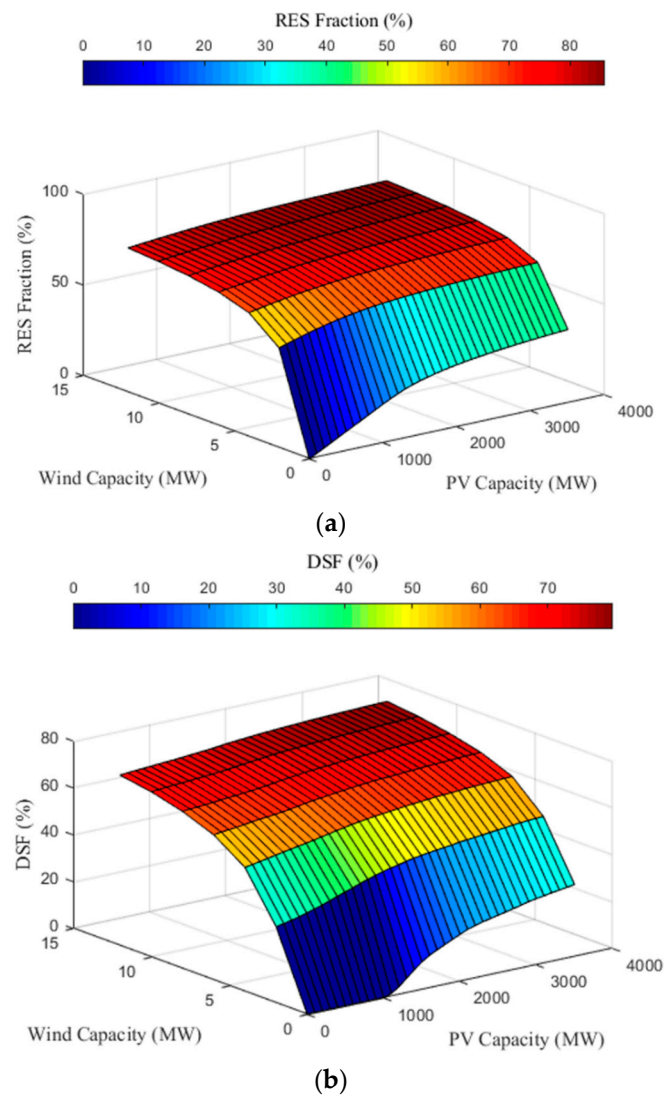


Figure 2. The technical parameters of different PV/wind hybrid system sizes in Gwanda: (a) renewable energy systems (RES) fraction and (b) demand supply fraction.

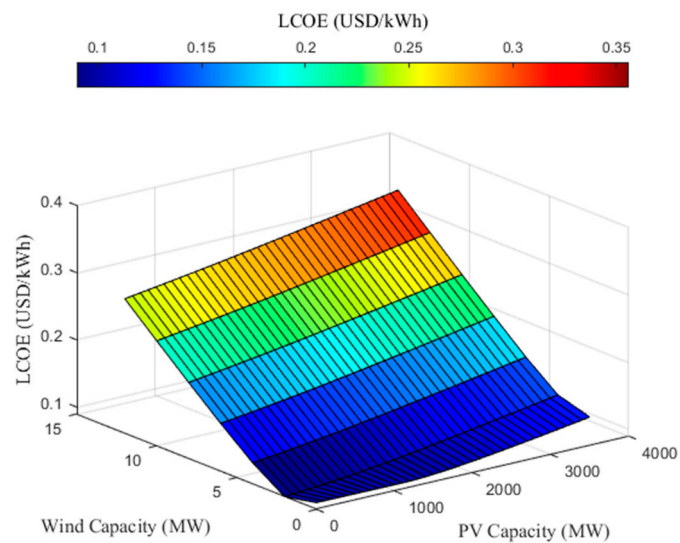
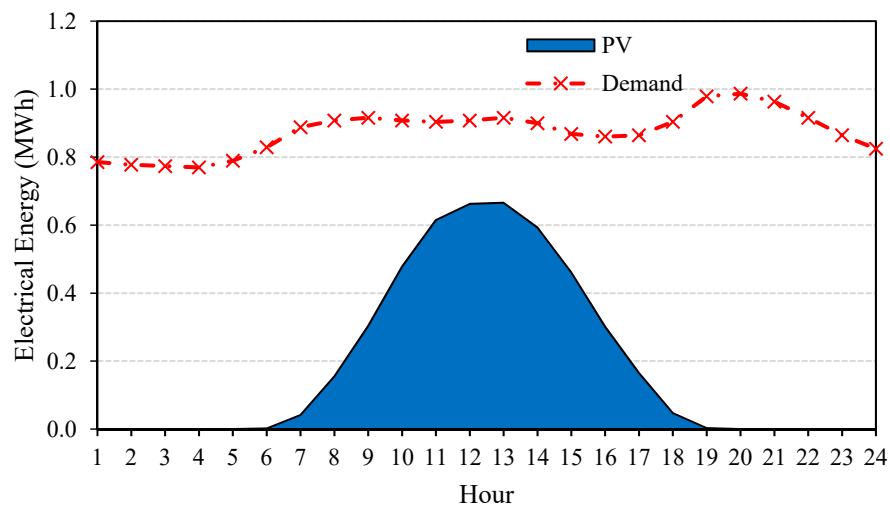
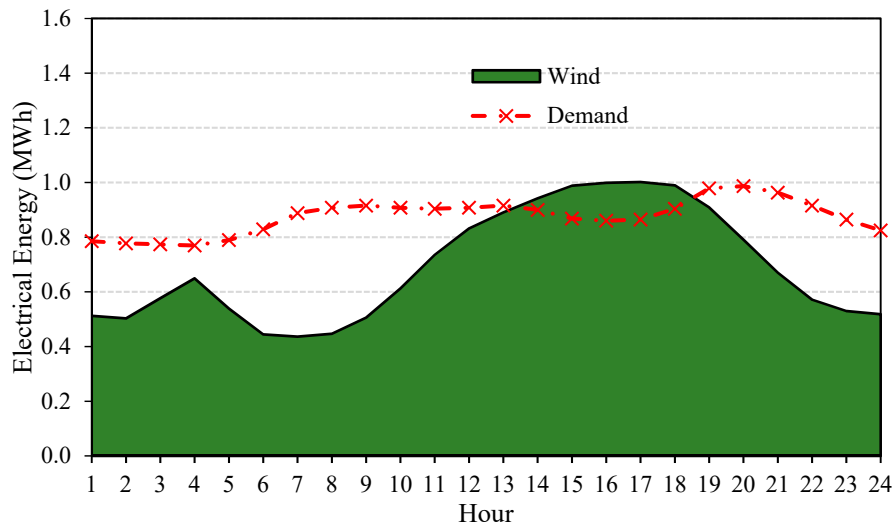


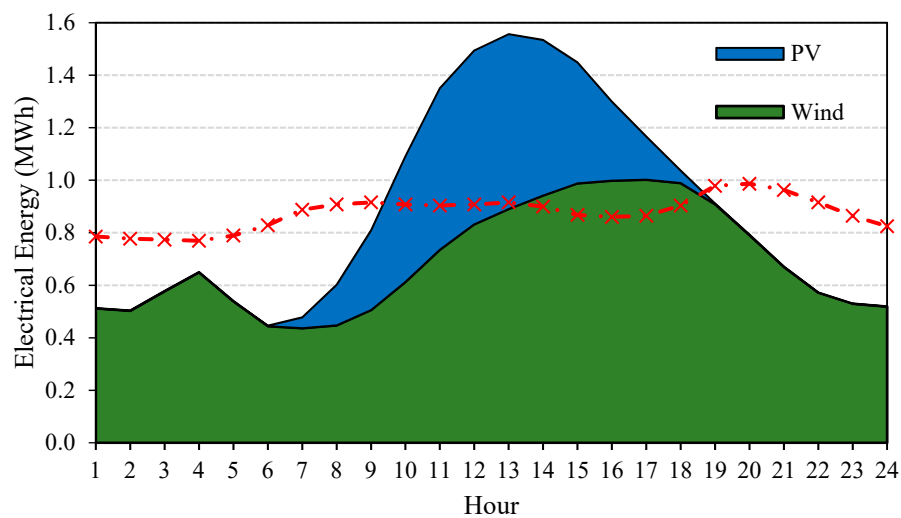
Figure 3. The levelized cost of electricity (LCOE) of different PV/wind hybrid system sizes in Gwanda.



(a)

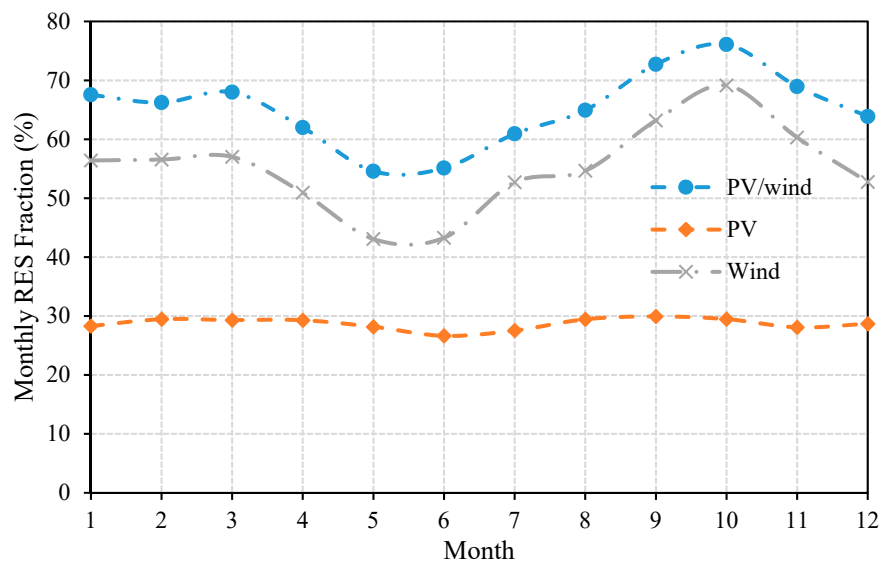


(b)

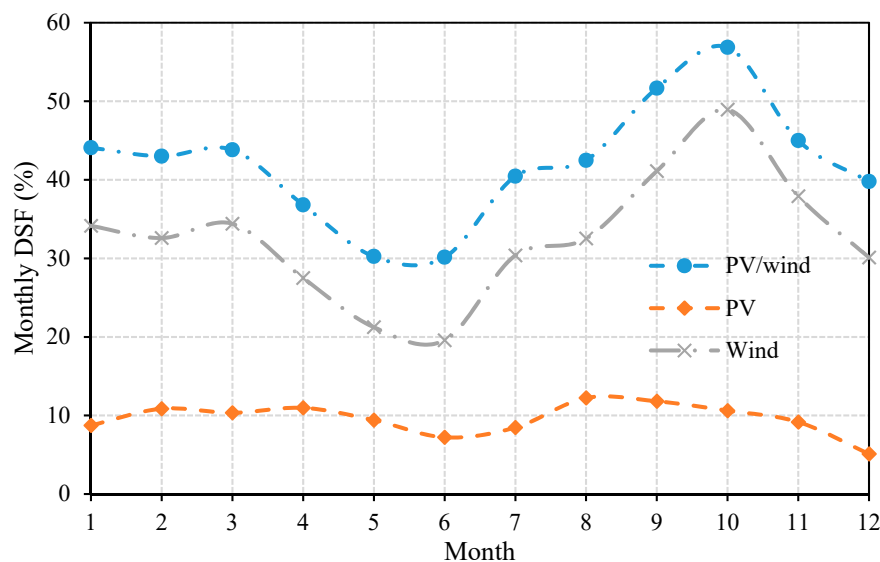


(c)

Figure 4. The average hourly energy generation from the maximum feasible: (a) PV system, (b) wind system and (c) PV-wind hybrid system in addition to the average hourly demand of Gwanda.



(a)



(b)

Figure 5. The monthly technical parameters of the maximum feasibly RESs: (a) RES fraction and (b) demand supply fraction.

Note that in Figure 5 the maximum RES fraction and DSF occur in October where this month has the highest wind resources and the highest solar resources throughout the year while the lowest RES fraction and DSF occur in May and June since these months have the lowest wind resources and the lowest solar resources. The proposed system in this study had better economic and technical feasibilities compared with similar renewable energy systems either standalone PV and wind systems or hybrid PV/wind systems with and without energy storage systems at similar geographic locations in Africa, as shown in Table 3.

Table 3. Techno-economic comparison of different systems at similar geographic locations in Africa.

| Paper | Location | System Type | LCOE (USD/kWh) | NPV (USD) | RES Fraction (%) |
|------------|--------------------|------------------------|----------------|---------------------|------------------|
| [63] | South Africa | Standalone PV | 0.16 | - | - |
| [44] | South Africa | PV/CSP | 0.16 | - | - |
| [43] | Sub-Saharan Africa | Standalone PV | 0.83 | - | - |
| [64] | Nigeria | Standalone PV | 0.40 | 590×10^3 | - |
| [13] | Zimbabwe | Standalone PV | 0.10 | 29.3×10^6 | - |
| [38] | Zimbabwe | Hybrid Wind/PV | 0.21 | - | 42 |
| [15] | Zimbabwe | Hybrid PV/Wind-Battery | 0.10 | 39.13×10^3 | 60.47 |
| [65] | Zimbabwe | Wind System | 0.13 | 7.8×10^6 | - |
| This study | Zimbabwe | Hybrid PV/Wind | 0.1 | 3.06×10^6 | 65.07 |

4. Conclusions

The hybridization between solar and wind systems partially solve the mismatch between the demand and the energy generation caused by the intermittency and the fluctuation of the resources and so increases the economic benefits of the RESs which makes it an attractive option to invest in. Solar and wind resources can complement each other and work in a synergistic way. Therefore, in order to prove that PV-wind hybrid system has better economics and performance compared with separate PV and wind systems, Gwanda city in Zimbabwe was the case study of this paper. The results indicate that the maximum feasible PV system in Gwanda-1.41 MW-has a RES fraction of 28.72% and NPV of 87×10^3 USD while the maximum feasible wind system-2 MW-has a RES fraction of 55% and NPV of 3×10^6 USD. On the other hand, the maximum feasible PV/wind system-2 MW wind and 1 MW PV-has RES fraction of 65.07% and NPV of 3.06×10^6 USD where it can be concluded that the PV-wind system did not only have the best technical performance but also the best economic benefit represented by the NPV and the PBP.

Author Contributions: Conceptualization, L.A.-G., R.S. and O.T.; methodology, L.A.-G. and O.T.; software L.A.-G.; validation, L.A.-G.; formal analysis, L.A.-G.; investigation, L.A.-G. and R.S.; resources, O.T. and M.F.; data curation, L.A.-G.; writing—original draft preparation, L.A.-G. and R.S.; writing—review and editing, L.A.-G., R.S., O.T. and M.F.; visualization, L.A.-G.; supervision, O.T. and M.F.; project administration, L.A.-G., O.T. and M.F. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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