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TECHNO-ECONOMIC FEASIBILITY OF PV/WIND-BATTERY STORAGE: CASE ANALYSIS IN ZIMBABWE

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ABSTRACT

The availability and the affordability of the energy resources in a country ensure the prosperity and development of the communities where energy is considered as the engine of the economic growth. Solar and wind resources are abundant and clean energy resources that can ensure both the availability and the affordability of energy. However, these resources are intermittent which decreases the reliability of such systems. The hybridization of solar and wind systems and the integration of energy storage system increase the reliability and the performance of the power systems. Therefore, this study aims to study the economic and technical feasibility of the integration of Zinc-Bromine and Lithium-Ion battery storage systems with PV/wind systems where Gwanda, Zimbabwe is the case study. The results indicate that the integration of Lithium-Ion and Zinc-Bromine batteries does not increase significantly the renewable energy fraction of the hybrid system where due to the high capital cost of these batteries, the feasible battery size is small. The proposed system which has the maximum renewable energy fraction- 60.47%- with the cost of electricity equals to 0.1 USD/kWh consist of 503 kW PV, 2 MW wind and 156.51 kWh Zinc-Bromine batteries where such system has a net present value of 39130 USD.

1. INTRODUCTION

Conservation of energy and natural resources, development of sustainable environment and energy systems are some of the main challenges that the world is currently facing. Zimbabwe is one of the Sub-Saharan Africa countries that are suffering from energy security issues. There has been a continuous increase in energy demand in Zimbabwe thus leaving huge energy deficit in which around 35% of the energy used in Zimbabwe is being imported from Democratic Republic of Congo (DRC), South Africa and Mozambique [1].

As a sustainable measure to curb for the current energy deficit in Zimbabwe, renewable energy systems could be utilized. The energy demand of the location, the economic situation and the geographical location of a region are the basic parameters required for the development of a suitable energy system. With over 4000 hours per year of sunshine at an average solar radiation of 5.5 kWh/m^2/day, Zimbabwe can be considered as a region with high solar resources [2]. Despite the availability of these renewable energy resources in Zimbabwe, none has been harnessed on a large scale. On a small scale, solar PV for irrigation and lighting and small windmills mainly for pumping water, exist in some farms [3].

Hybrid renewable energy systems with storage facilities can cater for intermittency which has been the major challenge that the renewable energy systems are facing. Some related issues such as reliability and grid stability mostly related to wind energy systems, have led to more research on renewable energy in which different methodologies have been utilized [4].

HOMER and MATLAB software has been employed for techno-economic as well as financial feasibility studies of these energy systems. The main goal of these studies is to determine the net present value (NPV), the cost of energy (COE) and the renewable energy source (RES) fraction [5]–[7]. Moreover, Ashok [8] determined a system that provided the lowest cost of electricity in a village in India using a Quasi-Newtonian method. Furthermore, Samu [9] did a feasibility study of a hybrid system without any storage facilities. Solar PV systems are feasible in every region in Zimbabwe and could be utilized on a large scale basis, which would help curb for the electricity deficit in Zimbabwe, in an environmentally friendly as well as sustainable manner [10]. The contribution of the present study is to carry out a techno-economic feasibility study of a hybrid PV-Wind-Battery-storage energy system of Gwanda location in Zimbabwe.

2. THEORY AND METHODOLOGY

2.1 PV Energy Model

The hourly energy generated from the PV power plant, E_P, can be estimated as,

$$E_P = \eta_{PV} \times I_T \times A_m \times N_m \times PF \quad (1)$$

where η_{PV} is the efficiency of the PV module which can be estimated using the methodology mention in [11], I_T is the global insolation on a tilted surface [Wh m^{-2}] which can be estimated using the methodology by Duffie and Beckman [12] , A_m is the single module area [m^2], N_m is the number of modules in the PV power plant, and PF accounts for the system losses which includes the shading, wiring, inverter and dust losses. In this study PF was taken 0.85 based on [13], [14]. In this study, PV modules from Canadian Solar company type CS6K-285M were used [15]. Moreover, global irradiation on horizontal surface, beam irradiation, diffuse irradiation and the ambient temperature data for Gwanda city were obtained using Meteonorm v7.1 software [16].

2.1 Wind Energy Model

The electrical energy produced by the wind turbine(s), E_w, can be estimated using Eq. (2).

$$E_w = \begin{cases} 0 & , V_Z < V_C \text{ or } V_Z > V_F \\ N \times P_W \times \frac{(V_C)^K - (V_Z)^K}{(V_C)^K - (V_R)^K} & , V_c \le V_Z \le V_R \\ N \times P_W & , V_R < V_Z \le V_F \end{cases} \quad (2)$$

where P_W is the rated electrical power of the wind turbine [kW], N is the number of turbines, V_C is the cut-in wind speed of the wind turbine [m/s], V_Z is the wind speed at hub height [m/s] which can be calculated using Eq. (3), V_F is the cut-out wind speed [m/s], K is the shape parameter of the Weibull distribution of the available wind speed and it can be calculated based on Justus theory using Eq. (4) and V_R is the rated wind speed [m/s]. Wind turbine with 2 MW of rated power from GAMESA company (G114-2.0) [17] was used in this study. Moreover, the hourly wind speeds at ground level for Gwanda city were obtained using Meteonorm v7.1 software.

$$V_z = V_G \times (Z/G)^{\alpha} \quad (3)$$

$$K = \{ (\sigma/\bar{V})^{-1.086}, \ 1 \le K \le 10 \quad (4)$$

where V_G is the wind speed at ground level [m/s], Z is the hub height of wind turbine [m], G is he ground level height [m], α is the wind shear coefficient where in this study it is taken as $1/7$ [11], $\bar{V}$ is the mean wind speed at hub height [m/s], and σ is the standard deviation of the wind speeds sample [m/s].

2.3 Battery Bank Model

In this study three Energy Storage System (ESS) scenarios will be studied and analysed namely without ESS, with Lithium-Ion and with Zinc-Bromine batteries where the optimal size of the PV/wind hybrid system will be found in each scenario. The ESS will be charged by the excess energy of the hybrid system, Figure 4 shows the energy flow chart of the hybrid system. The depth of discharge and the overall efficiency are the only ESS characteristics considered in this study. Table 1 shows the DOD and the overall efficiency for the Lithium-Ion and the Zinc-Bromine batteries.

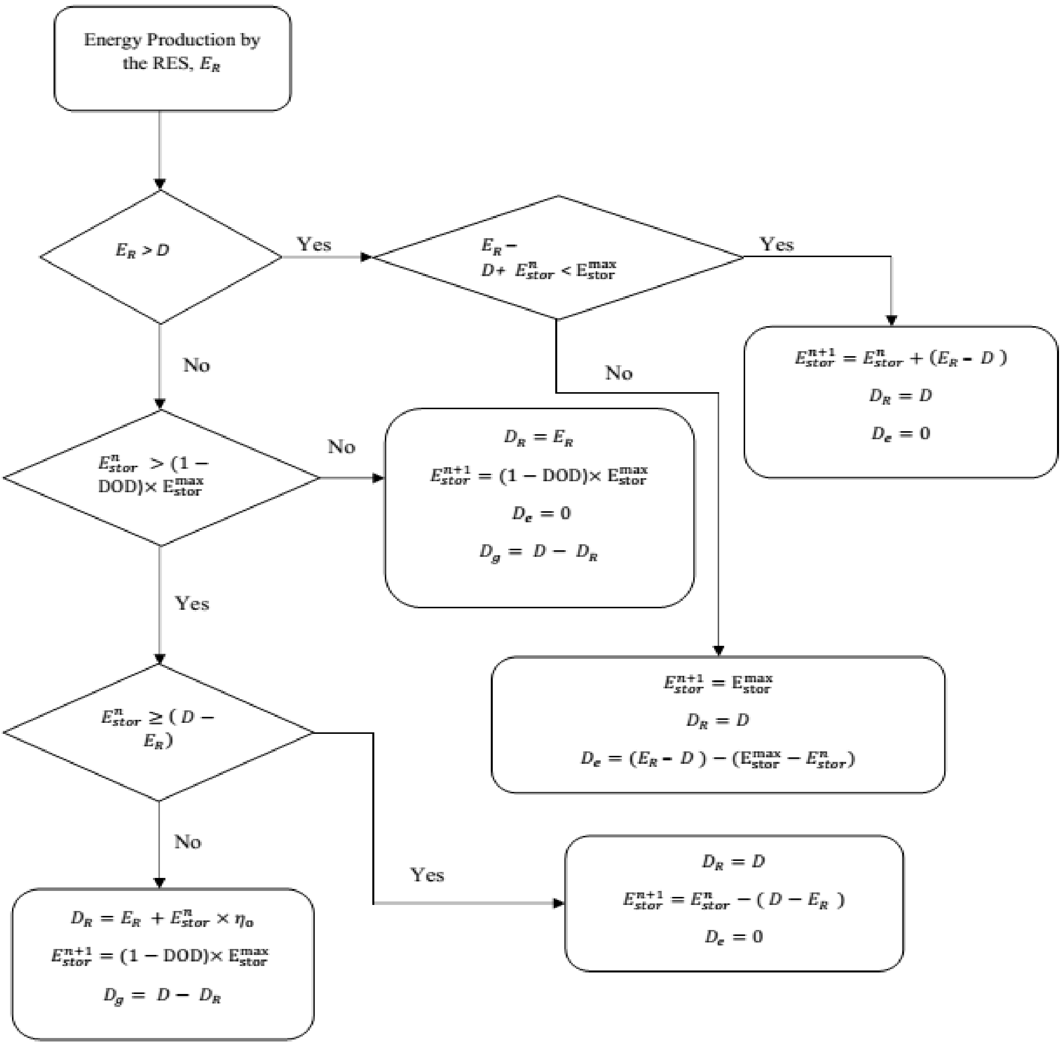

Figure 1. The RES energy flow chart in the presence of ESS where E_R is the hourly energy produced by the hybrid system [kWh], E^n_{stor} is the hourly energy stored in the ESS at time n [kWh], DOD is the depth of discharge of the ESS, E^{max}_{stor} is the ESS size [kWh], η_o is the overall efficiency of the ESS, D_g is the hourly energy consumed from the grid [kWh] and D_e is the hourly excess energy from the hybrid system [kWh].

Table 1. Technical Specification of the Lithium-Ion and Zinc-Bromine Batteries [18], [19].

Parameter	Lithium-Ion	Zinc-Bromine
Round-Trip efficiency (%)	95	72
DOD (%)	60	80

2.4 Performance Assessment of the RES

The RES Fraction (RF)- which represent the annual fraction of demand met by the RES- can be used to inspect the matching between the energy generation from the RESs and the demand. RF can be calculated as,

$$RF = \frac{D_R}{D} \quad (5)$$

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 [9] while the hourly load profile for Gwanda city was approximated to be like the profile of a city in Zambia [20].

2.5 Economic Assessment of the System

In this study, two parameters are used to assess the economic feasibility of the energy systems namely the levelized cost of electricity (LCOE) and the Net Present Value (NPV). LCOE of the RES can be calculated using Eq. (6) where in order to incorporate the effect of the mismatching between the energy generation and the demand, the demand met by the hybrid system was used instead of the energy generation where it is assumed that the excess energy is pumped into the grid for free. Whereas in order to account for the cost of electricity provided by the grid to the system the overall Cost of Electricity (COE) for Gwanda city is calculated using Eq. (7).

$$LCOE = \frac{C+\sum_{t=1}^{L}\frac{M}{(1+d)^t}}{\sum_{t=1}^{L}\frac{D_R}{(1+d)^t}} \quad (6)$$

$$COE = \frac{D_R \times LCOE + G_T \times D_g}{D} \quad (7)$$

where C is the capital cost of the RES [USD], M is the yearly fixed 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 d is the annual discount rate. Table 2 shows all the economic parameters used in this study.

Table 2. The economic parameters of the PV and wind systems in addition to the grid tariff and the annual discount rate for Gwanda city, Zimbabwe.

Parameter	**Value**	**Reference**
PV system capital cost ($/kW)	1533	[21]
Wind system capital cost ($/kW)	1516	[21]
PV maintenance cost ($/kW)	24.68	[22]
Wind maintenance cost ($/kW)	39.53	[23]
Lithium-Ion Battery Cost ($/kWh)	495	[24]
Zinc-Bromine Battery Cost ($/kWh)	250	[24]
System's lifetime (Years)	20	[18], [19], [25], [26]
Grid tariff ($/MWh)	100	[9]
Annual discount rate (%)	7.2	[27]

3. Results and Discussion

Renewable energy systems can be used as suitable energy generation sources instead of fossil fuels which will contribute significantly to the mitigation of Greenhouse Gases (GHGs) as well as ensure the energy security of the countries. However, the intermittency of renewable energy resources makes it unreliable and also affects the quality of power generation. The hybridization of different renewable energy systems and the integration of ESSs can increase the reliability of the energy systems and enhance the quality of power generation. The cost of the ESS is one of the major drawbacks for the use of battery storage systems in renewable energy applications where it affects the economic feasibility of RESs. In this study, the techno-economic feasibility of the hybrid system with Lithium-Ion and Zinc-Bromine is compared with the system without ESS. Table 2 shows the technical and economic parameters of the optimal sizes of PV/wind hybrid system with no ESS, with Lithium-Ion and with Zinc-Bromine batteries in Gwanda that maximize the RES fraction with COE equals to the local grid tariff.

Table 3. The optimal sizes of PV/wind hybrid system with no ESS, with Lithium-Ion and with Zinc-Bromine batteries in Gwanda, Zimbabwe in addition to their economic and technical parameters.

Configuration	No ESS	Lithium-Ion	Zinc-Bromine
PV Capacity (MW)	0.544	0.331	0.503
Wind Capacity (MW)	2	2	2
Battery Capacity (kWh)	-	279.75	156.51
Energy Produced (MWh)	6815	6518.1	6757.8
Excess Energy (MWh)	2184	850.25	2143.67
Energy Met by the Grid (MWh)	3034	1962.84	3029.7
Energy Production to Demand Ratio (%)	88.9	85	88.16
Capacity Factor (%)	30.58	31.92	30.82
RES Fraction (%)	60.42	59.10	60.47
COE ($/kWh)	0.1	0.1	0.1
NPV (k$)	0	138.48	39.13

Notice that in Table 2, the integration of Lithium-Ion and Zinc-Bromine batteries decreased the feasible PV capacity from 544 kW to 331 kW and to 503 kW respectively. In the Lithium-Ion scenario, the drop in the PV capacity caused the drop in the RES fraction due to the increase in the capital cost of the system with low revenues from the integration of the battery. While in the Zinc-Bromine scenario, the RES fraction was slightly increased where the drop in the PV capacity was compensated by the energy stored in the battery. The main factor that controlled the effect of the integration of the batteries is the capital cost even though both batteries have different DODs and different round-trip efficiencies. Moreover, notice that in both ESSs scenarios the NPV value of the systems increased even though the RES fraction- which affects the revenues- was decreased in the Lithium-Ion scenario and slightly increased in the Zinc-Bromine. The main reason for this increase is due to the decrease in the PV capacities which have high capital cost with low capacity factor- 15.91%- compared with wind systems- 34.57%- in Gwanda.

In all the scenarios analysed in this study, the electricity grid meets almost 40% of the demand even though the ratio between the energy production and the demand is larger than 85%. The main reason for this is the mismatch between the energy generation and the demand and also as aforementioned, the capital cost of the batteries prevents the wide use of ESSs to utilize and reallocate the excess energy from the RESs. Figure 2 shows the hourly energy produced by the hybrid system's components in addition to the hourly energy stored in the ESSs that can be utilized and the hourly demand of Gwanda for the three ESS scenarios.

4. Conclusions

The intermittency and the fluctuation of the solar and wind resources cause the mismatch between the energy generated and the demand, the hybridization between these two systems and the integration of energy storage system can enhance the matching. In this study, the optimal sizes of PV/wind hybrid system with three ESSs scenarios namely without ESS, with Lithium-Ion and with Zinc-Bromine batteries are to be determined where Gwanda, Zimbabwe is the case study. The optimization of the hybrid system was based on maximizing the RES fraction with COE equals to the grid tariff. The results indicate that the integration of Lithium-Ion and Zinc-Bromine batteries does not increase significantly the RES fraction of the hybrid system where due to the high capital cost of these batteries small battery capacity can be integrated without affecting the economic feasibility of the system. The proposed system which has the maximum RES fraction with COE equals to 0.1 USD/kWh consist of 503 kW PV, 2 MW wind and 156.51 kWh Zinc-Bromine batteries where such system will have RES fraction of 60.47%, the capacity factor of 30.82% and NPV of 39130 USD.

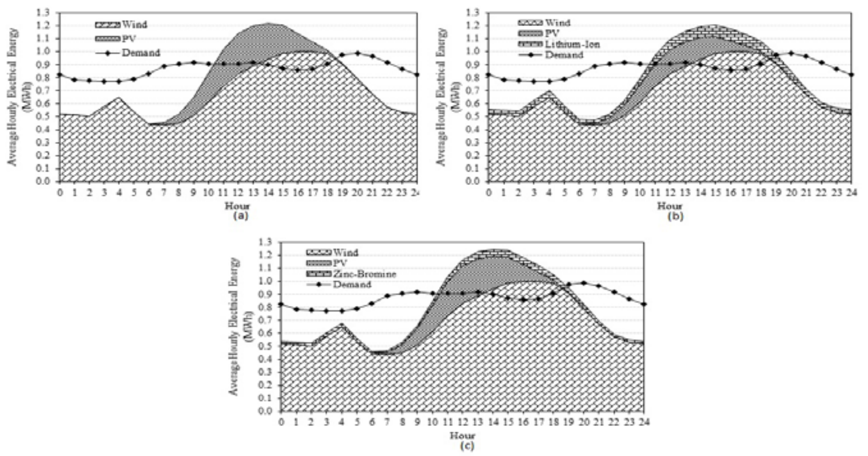

Figure 2. The hourly energy produced by the PV and wind systems as well as the hourly energy available in the ESSs and the demand of Gwanda in the three ESS scenarios: a) without ESS b) with Lithium-Ion batteries c) with Zinc-Bromine batteries.

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