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Optimization of the design and manufacture of a solar-wind hybrid street light

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Abstract

The demand for electricity has escalated and cannot be fulfilled by conventional energy sources alone. There has been a rising demand to seek new renewable energy sources. Although solar and wind energy are the most cost effective renewable energy sources, they are unreliable due to the sporadic nature of their occurrence, if implemented as standalones. In Zimbabwe, solar street lighting has been implemented since 2014 as a solution to the erratic power supplies and outages. Wind potential in Zimbabwe has been identified at elevated heights, with Gweru having the maximum power density of 115 W/m^2 at 50 m hub height. This paper presents the optimization of the design of a hybrid renewable energy system (HRES) of solar and wind energy to power a 160W streetlight. The system consisted of a wind turbine, photovoltaic modules, charge controller, battery bank and lights. The system sizing was done in Excel using wind and solar data obtained from the database, HOMER Software Package and PVSyst. The 3D streetlight was modelled using Inventor Professional and a working prototype was manufactured. The results showed that the HRES reduced the energy storage requirements by 38.75% with an overall cost reduction of 14.4%, relative to a standalone solar streetlight. The diffuser effect to the turbine was experimentally assessed, showing 69.3% increase in turbine power output and a 50% decrease in energy storage requirements. Further research can be carried to improve the reliability for standalone systems.

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1. Introduction

Energy requirements in almost all societies has been increasing and the consumption has not matched the ever increasing demands hence the need to explore alternative forms of energy to augment supplies from national grids [1]. The demand for electricity has been supplemented mostly by fossil fuels such as coal, oil and natural gas. In Zimbabwe 45.6% of energy comes from fossil fuels with the rest coming from hydro-electric generation [2]. With the high impact on the world economy brought on by increasing price fluctuation of fossil fuels due to geopolitical issues and/or environmental disasters, the search for solutions that promote the sustainability of power supplies has equally grown in importance. Sources have increased interest in renewable energy, solar and wind energy being the most prominent sources of them. The field of hybrid solar-wind has experienced a remarkable growth for the past two decades in its widespread use of standalone to utility interactive solar-wind systems commonly in fields such as street lights, water pumps, house electrification and power stations [3]. Since 2014. The Government of Zimbabwe embarked on the solar lighting project in small urban areas with the aim to address increased power shortages [2].

Data collected from monitoring sites in Chimanimani, Chivhu, Karoi, Mt Darwin and Rusape in Zimbabwe, and readily available on the world database, appeared that as much as 33% of Zimbabwe had sufficient wind which can be used for viable and sustainable wind power generation [4]. However, the wind power density for Zimbabwe is generally low for economic large scale power generation, though some considerable potential exists in the Midlands province for applications such as water pumping that can do with low wind speeds of 2.5m/s [5]. Hybrid Renewable Energy Sources (HRES) can be used to overcome this drawback. The significant characteristic of HRES are in the combination of solar-wind energy sources to make proper use of the operating characteristics and to obtain efficiencies higher than that could be obtained from a standalone source [6]. Lack of wind but more sunlight in summer and lack of sunlight but more wind in bad weather make standalone wind or solar energy systems unreliable. Wind and solar are complementary resources thus a hybrid will ensure a continual supply of energy even during night times, thus enhancing increased reliability. This research focused on optimizing the design and development of a prototype hybrid system using locally available and sustainable materials to power a 60 W LED light. The developed model was also targeted to have good reliability throughout the seasons. Apart from conceptualizing on various alternatives, the design was accomplished through sizing of a wind turbine diffuser in order to determine its effect on the turbine efficiency.

2. Background and literature review

Based on wind and solar data, the chosen site for wind solar hybrid street lights was Gweru situated along the road and railway between Harare and Bulawayo, Zimbabwe's largest and second largest cities. Gweru has become a busy trading centre with reasonable industrial development due to its proximity to the Great Dyke where most natural minerals are found in the country. Its products include ferrochrome, textile, dairy foods, footwear and building materials. The surrounding area has rich deposits of gold, chromium, iron, asbestos and platinum and are also well known for vibrant farming activities in beef cattle, crop farming and commercial gardening of crops for the export market. Each conventional streetlight spends 1825 kWh 10 years. According to the standard thermal consumption (400g /kWh), the standard coal consumption will be 7.3 tons. So, a city center will consume 876,000 tons of standard coal just in 10 years, letting out 3 million tons of carbon dioxide, 17,500 tons of SO_2, 13,000 tons of nitrogen dioxide, and so much powder and impurity. However, the use of solar-wind hybrid will significantly reduce this pollution [7]. For all load demands, the effective energy cost for a PV-wind hybrid system is always lower than that of a standalone solar system [8]. The hybrid combination lowers energy storage requirements and thus lower effective costs. The installation of solar-wind hybrid street lights would reflect the city's modernization as it is economic to use and produce power by itself. After the construction of the one-time investment, the city would realize a long-lasting benefit. Changing the conventional streetlight system laid on the underground cable power supply way saves a lot of manpower and financial resources. Solar power is a growing major energy source responsible for sustaining power supplies especially if the resource is well tapped to complement power supplies from national grids. The sun gives out its energy in the form of electromagnetic radiation and after reaching the earth surface it is converted to other types of energy used for many purposes [9]. According to the United Nations Development Program in its 2000 World Energy assessment that annual potential of solar energy was 4.375-138.436x10^{14}kWh [10]. This is large compared to a total world energy consumption of 104,426x10^{9} kWh in 2012 [11], thus demonstrating great potential.

Photovoltaics are the direct conversion of light into electricity at the atomic level by photoelectric effect on semiconductors [12]. A number of solar cells are electrically connected to each other and mounted in a support structure to form a photovoltaic module and these modules can be connected to form an array [12]. Fig. 1 (a) shows I-V and P-V curves of a solar panel with the 3 characteristic points (short circuit, I_{sc}, maximum power, P_{max}, and open circuit points, I_{oc},) labelled. Monocrystalline cells (Fig. 1 (b)) have the highest efficiency rates of 15% - 21.5% since they are made out of the highest-grade of silicon while polycrystalline cells (Fig. 1(c)) are less efficient with 11% - 17% efficiency [13]. The best absorption of solar radiation on a panel occurs when the striking angle is 90°.

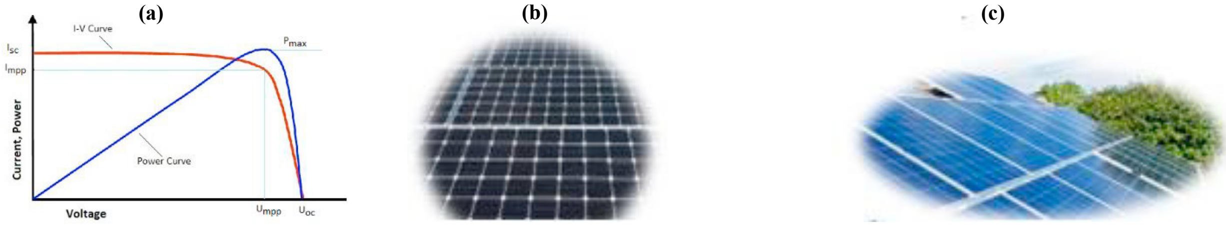

Fig. 1 (a) I-V and P-V curves of a solar cells, (b) Monocrystalline solar cells, (c) Polycrystalline solar cells.

Wind power is also another renewable resource that has stimulating potential for the future. Wind is formed by the sun's uneven heating of the earth's surfaces, the irregularities of the earth's surface, and the rotation of the earth. Whereas, the land absorbs more heat than water, the uneven heating of the earth's surface causes flow of currents from regions of high heating to regions of low heating, giving rise to wind. Energy available in wind is basically the kinetic energy of large masses of air moving over the earth's surface. The power coefficients of all turbines have a theoretical maximum value commonly referred to as the Betz Limit which is equal to 16/27 approximated as 59% [14].This is the maximum efficiency that a turbine can attain using equation (1). Examples of wind turbines are the Horizontal Axis Wind Turbine (HAWT) and the Vertical Axis Wind Turbines (VAWT). Wind turbines normally consist of 2 or 3 blades on a rotor connected to a generator to produce electricity. Power generation starts at the machine at wind speeds of about 3-7 m/s and shuts off the machine at about 25 m/s. Turbines do not operate at wind speeds above 25 m/s because they may be damaged by the high winds [14]

$$P = \frac{1}{2} C_p \rho A V^3 \tag{1}$$

Diffuser Augmented Wind turbines (DAWT) are those altered with a cone shaped wind diffuser which is used to increase the efficiency of converting wind energy to electrical power. Power extraction by a wind turbine occurs at the rotor surface. Due to the pressure fall over the rotor plane which produces a force on the rotor on the inward flow, the power extraction thrusts. This lift force is a result of a pressure difference between the upper and lower part of the diffuser, which can be numerically modelled as a ring vortex. Using the Biot-Savart law this is coupled to an induced velocity at the rotor plane, yielding an enhanced mass flow [15].

HRES is a combination of renewable and conventional energy sources. It may also combine two or more renewable energy sources that work in standalone or grid connected mode [6]. The 2 energy sources are an efficient way of generating energy and achieving energy balance. Hybrid energy systems are commonly used in remote areas for power generation. Solar wind street lights are made up of; wind turbine, inverter, battery bank, solar module, charger controller, pole and LED lights. The charger controller limits the rate at which electric current is added to or drawn from the electric batteries. In Zimbabwe, the use of wind technology as a renewable energy source on its own has limitations due to the low average wind speeds [4], hence the need to develop a system that can tap from dual sources of the sun and wind. The wind turbine complements the solar PV cells during periods of reduced solar radiation and vice versa. However, for maintenance the wind turbine technology requires constant monitoring and maintenance of rotating parts. The research was motivated by the need to address issues of inadequacies in grid national power supplies, complaints of poor lighting at night and the need for cleaner and environmental technologies.

3. Methodology and materials

The process of designing a wind diffuser and sizing a PV-wind hybrid system involved the conceptual implementation of a number of electrical and mechanical subsystems to create a machine capable of converting the wind and solar contained energy into useful electrical energy. There were different approaches that were used in line with wind turbine design and accordingly there were also a number of issues that needed to be taken into account. Design guidelines were taken into consideration for application of this research [16]. The methodology was followed through various stages such as; determining the application, review of previous applications, selection of topology, preliminary load estimation, development of a 3D experimental model, prediction of performance, evaluation and optimization of the developed concept. For the sizing of the turbine and PV array (hybrid sizing), the methodological approach applied for electrification through a hybrid system, combined photovoltaic and wind energy through the following stages [9]; identification, field survey and analysis of energy demand for the streetlight, analysis of the wind and solar radiation potential on the geographical region of the city using Excel software and selection of the best configuration option of the hybrid system that met quality, lower cost and electricity demand of the streetlight.

4. Design, analysis and results

The results obtained were analyzed in Excel and presented as tables and graphs, showing the trend that was obtained. Analysis was done comparatively between standalone PV and hybrid systems with and without a diffuser. Zimbabwe wind power density varies from 15W/m^2 in Kariba to 115W/m^2 in Gweru at 50m hub height. Average wind speed at 15 m height was obtained using the Wind Power Law with the wind shear α = 1/7 (for terrain with several buildings). Fig. 2 shows the Average Wind Speed (AWS) at 15 m height. According to the data derived from the figure in the Gweru region, the maximum approximated mean monthly wind speed was 4.215 m/s.

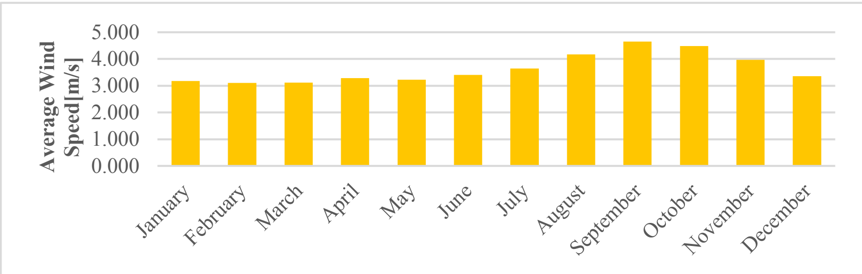

Fig. 2. Monthly Average Wind Speed (AWS) data at 15 m height.

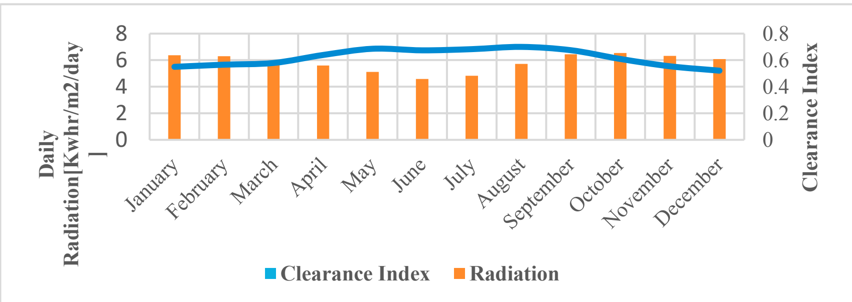

Fig. 3. Monthly Average Solar Global Horizontal Irradiation (GHI) data.

The monthly solar radiation given by the HOMER software is shown in Fig. 3. The estimated solar radiation had a maximum value of 6.370 kWh/m^2/day in January, the lowest value of 4.580 kWh/m^2/day in June, and an annual average of 5.81 kWh/m^2/day. The HOMER software also introduced the clearance index from the target site, showing high values during winter months (Apr-Aug) and low values in the summer months (Sept-March) where mostly the skies were cloudy. The site location was surveyed and using the data obtained from the SolarLux Company, a standard street light of 80W LED gave a good illumination to the area. The LED was purely DC current and projected to work for 12 hours (6pm - 6am). Thus, the load demand of the system was constant. The developed concept consisted of a static diffuser and a rotating HAWT for power generation. In order to determine the optimal solution, the different concepts were compared according to how much they met the desired result through weighted objectives.

5. Design optimization and discussion

The hybrid system sizing was done using Excel spreadsheet. In the model, hourly simulation of both wind and solar were presented to give hours of power output for each source. These were simulated for each hourly load giving the results shown in Fig. 4 (a) and (b).

(a)

PV specification	250W
Turbine Specification	300W
Battery Capacity	6240Whr
Days of Autonomy	3 days
Annual Renewable Energy Fraction(Reliability)	0.984
Fraction Damped	0.25

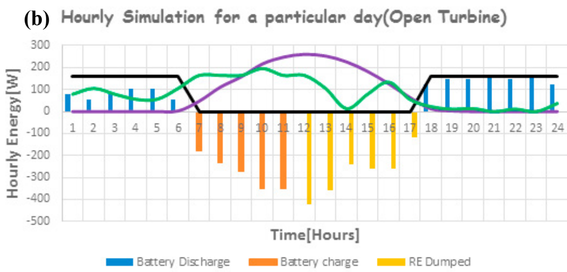

Fig. 4 (a) Hybrid Specification without diffuser; (b) Hourly simulation for a particular day in Ms Excel

The results showed that during times when the wind and solar power did not meet the load demand (160W), the battery would discharge to meet that demand. Inevitably, approximately 25% of the energy was dumped during the day because the battery source was full. The percentage of energy dumped (25%) was less than the maximum accepted of 30%. The system had 98.4% reliability meaning it had only 3 days in a year which it might fail to meet the load demand. The 300W Atlantis Windkraft with 3 blades was selected for the wind turbine. From the PV solar model, 640 Whr battery capacity was required per day. The overall effect of the wind turbines with and without diffusers were compared for wind speeds of 6 – 20 m/s showing a significant difference in power generated. Table 1 shows the hybrid specification with diffuser while Table 2 shows the HRES and standalone PV system specifications.

Table 1. Hybrid specification with diffuser

PV specification	240W
Turbine Specification	300W
Battery Capacity	6240Whr
Days of Autonomy	3 days
Annual Renewable Energy Fraction(Reliability)	0.9824
Fraction Dumped	0.256

Table 2. HRES and Standalone PV system specifications

	Specifications	
Component	***PV-Wind Hybrid***	***PV Standalone***
Battery Capacity	245 Ah / 24 V	400 Ah /24V
Power Source	300W Wind turbine 2x125W PV Modules	2x210W PV Modules
LED Streetlights	80W/ 24V	80W/ 24V
Charge Controller	20A/24V Solar-Wind Hybrid (PMW)	20A/24V Solar Charger Controller (PWM)

The percentage decrease in battery bank = (400-245)/400 =38.75%. Thus, the HRES reduced the energy storage requirements by 38.75% relative to a standalone PV system. A 2 m stand to hold the wind turbine, solar panel and battery bank was designed and developed with a cage to accommodate the batteries. The exploded components and their connection are shown in Fig. 5(a) while Fig. 5 (b) shows the 3D model developed using Inventor Professional. The solar PV cells were designed in such a way that they could be tilted effectively to allow for self-cleaning during maintenance.

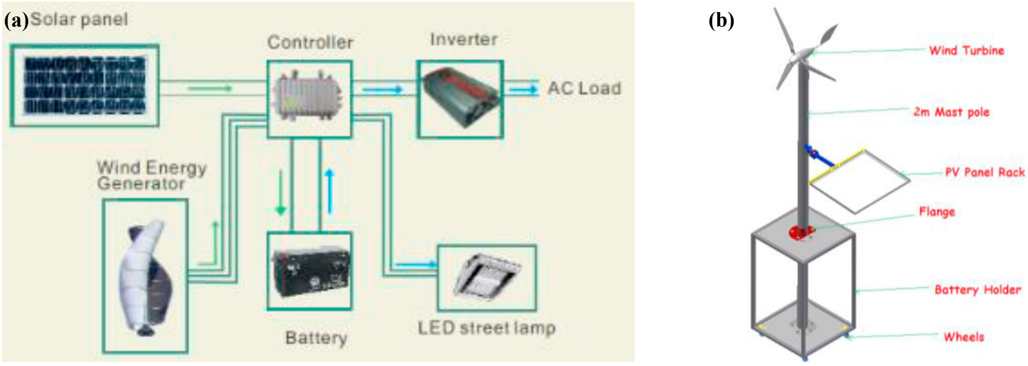

Fig. 5 (a) Components of the hybrid system; (b) 3D CAD Model of the prototype solar-wind streetlight

6. Conclusions

The supply of electricity in Zimbabwe has been erratic due to reduced generation, load shedding and general increases in demand, thus prompting the need to find alternative sources of energy to power such utilities as streetlights. The research focused on the design and development of a solar-wind hybrid streetlight for Gweru to power 2 LED lights of 80W each. The design achieved 98.4% reliability and a cost of $4350 at a levilised energy cost of 17.5 cents/kWh. The inclusion of a diffuser on the wind turbine increased the turbine power output by an average of 69.3% and this resulted in a 15% decrease in the solar panel size and 50% reduction in the battery bank. The turbine was recommended to be placed at least at 15m above the ground for max efficiency while the battery bank can be fixed into the ground. Implementation of such innovation using locally available and sustainable materials can assist countries to reduce the ever increasing demand for power from national grids.

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