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FEASIBILITY STUDY AND DESIGN OF A SOLAR-WIND HYBRID POWER SYSTEM IN RWANDA

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ABSTRACT - *The government of Rwanda aims to increase electricity access to 100% by 2024, with 52% connected to the national grid and 48% using off-grid technologies. One potential solution is to adopt renewable energy, particularly a solar-wind hybrid power system. The goal of this research project is to design and carry out a feasibility study of a hybrid solar-wind system for electrifying Gatwa village in Nyamagabe District, which has been found to have sufficient solar radiation and the strongest wind. The study collects wind and solar data from meteorological stations in various regions of Rwanda. To meet the village's electrical energy needs, 88 PV modules, 2 wind turbines, 25 batteries, 20 solar charge controllers, 14 wind charge controllers, and an inverter will be needed. For installation, the suggested hybrid system needs copper wires with cross-sectional areas of 10 mm2, 25 mm2, 32 mm2, and 70 mm2.*

***Keywords*: Renewable Energy, Wind and Solar Energy, Hybrid Solar-Wind System, Rural Electrification, MATLAB Simulation.**

1. INTRODUCTION

Rwanda is a landlocked country in East Africa with a growing economy and increasing energy demands. Due to Rwanda is physically composed of so many hills, building transmission as well as distribution lines and even increasing the country's electrical infrastructure, is expensive in most rural regions. The current percentage of households connected to the National grid is 50.9% and off-grid connection percentage is 23.6% and mostly concentrated in towns [1].

In rural areas, expanding the power system and connecting the national grid is expensive due to the geographical situation of Rwanda; building distribution lines is expensive and slow undertaking due to many hills that made the country.

Given that renewable sources are located in the regions where the energy is to be utilized and hence require less transmission and distribution lines, may renewable energy resources be the most beneficial option? Despite efforts to expand the national grid, there are still significant challenges in providing electricity to all regions, especially rural and remote areas. This lack of access to electricity hampers economic development, education, healthcare, and other essential services. Fortunately, the Rwandan government wants to expand the population's access to energy to 1000% by 2024 where 70% households will be connected to the grid while around 30% will be using off grid solutions, and renewable energy sources are being investigated. [1]

Hence, the aim of this paper is to conduct a feasibility study of a solar-wind hybrid power system in Rwanda for providing a reliable and cost-effective electricity supply, especially to underserved areas.

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2. SOLAR PV SYSTEM

2.1. SOLAR PANELS

Solar panels are devices that generate electricity from solar radiation. They are a key component of solar energy systems and have become a very popular renewable energy source in recent years.

Solar panels collect the energy from the sun by utilizing the photovoltaic effect, which is the potential of some materials to produce an electric current when exposed to light [2].

The most common type of PV panel consists of interconnected PV cells, typically constructed from silicon. These solar cells consist of multiple layers of semiconductor materials that generate an electric field when exposed to sunlight [3] [4]. When light photons (particles) hit the surface of solar cells, they transmit that energy to the material, which causes the electrons to flow and produce an electric current. Solar panels are generally linked in an array or bigger system to improve performance. To produce greater voltages or currents, a panel can be joined to others in a series or parallel configuration. This allows for the production of electricity suitable for various applications, from powering small electronic devices to supplying electricity to homes, businesses, and even entire power grids [4] [2]

2.1.1. SOLAR CELL

A solar cell is an electrical device that uses the PV effect to directly transform light energy into electricity. A device whose electrical characteristics, such as current, voltage, or resistance, change in reaction to light is known as a photoelectric cell. The modules, also known as solar panels, are made up of individual solar cell units [5] [6].

2.1.2. EQUIVALENT SOLAR CELL CIRCUIT

Figure 1.2 below shows a simplified schematic of the equivalent of an ideal SC., where voltage and current loss are not taken into consideration

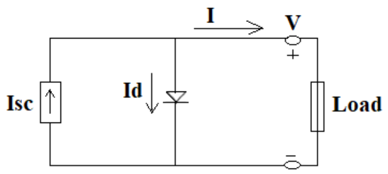

Figure 2.1: Simplified diagram of an equivalent solar cell circuit

Kirchhoff's law is applied to calculate the short circuit current through the figure above.

$$I_{sc} = I + I_o\left(e^{\left(\frac{q^v d}{mKT}\right)} - 1\right) \qquad (2.1)$$

Where: **Io** is the reverse saturation current of the diode; **Vd** is the e junction voltage; **m** is the ideality factor of diode. The diode Current (***I_d***) is calculated as follows:

$$I_o\left(e^{\left(\frac{q^v d}{mKT}\right)} 1\right) \qquad (2.2)$$

The expression (2.2) may be used to determine two operating points of the solar cell, as follows:

For short circuit:

(V_d = zero leading to I_d = 0),

thus: $I_{sc} = I$ (2.3)

For open circuit:

$(\mathrm{Vd} = \mathrm{Voc}, \mathrm{I} = 0)$ (2.4)

From equation (2.2), we get the open circuit voltage V_{oc}:

$$V_{oc} = \frac{mKT}{q}\ln\left(\frac{I_{sc}}{I_0} + 1\right) \qquad (2.5)$$

The two parameters that the manufacturer provides, open circuit voltage (Voc) and short circuit current (Isc), are crucial for drawing the I-V curve (Figure 2.10), that is used to predicting the SCs' capacity of operating at different temperatures, voltage loads, and insolation levels. e equation provides the power produced by the cell is $P = IV$.

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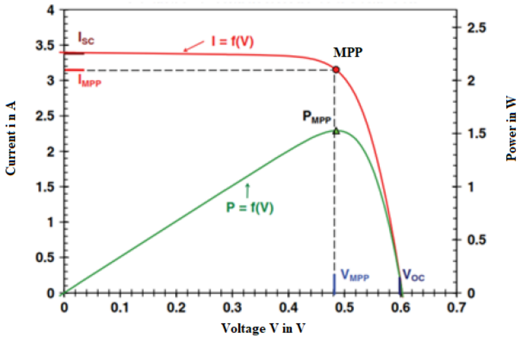

Figure 2.2: I-V and P-V curves of a solar cell. Source: [7] [8]

On this curve, the most significant point is the MPP (maximum power point), or the point at which maximum power output from the module occurs. The outputs of module [voltage and current at maximum power point (VMPP & IMPP) are always located where the curve starts to bend [6] [8].

The Fill Factor (FF) is an additional parameter that indicates the degree of deviation of the I-V curve. The maximum power that can be achieved divided by the product of the open-circuit voltage and short-circuit current is known as the fill factor, and is given by:

$$FF = \frac{I_{MPP}.V_{MPP}}{I_{SC}.V_{OC}} \qquad (2.6)$$

The power density provided at the operational point as a percentage of the incident light power density Ps is the conversion efficiency (η) of SC which may be obtained using the following formula:

$$\eta = \frac{FF_{IMPP}.V_{MPP}}{P_S} \qquad (2.7)$$

2.2. WIND ENERGY SYSTEM

Although Rwanda's potential wind power in some regions may supply energy with potential applications including water pumping, and electricity generation, it is currently not totally exploited for power generation. The findings of a study conducted across the country on wind speed distribution are as follows:

- The wind's direction change from 40º to 130º
- The wind speed change from 2m/s to 9.5 m/s

Rwanda's synoptic stations and data summaries are managed by the National Meteorological Service

WORKING OF WIND POWER SYSTEM

wind energy is another renewable energy source that may be used to produce electrical energy with the help of generators and wind turbines. Wind power systems convert the kinetic energy of circulating air, or the energy in the wind, into a different type of useful power, usually mechanical or electrical. Wind turbines are the devices wherein this conversion takes place. When an air current moves through the area swept by a wind turbine's rotor, energy is transformed. [4] [9]

The following equation shows how a wind turbine's power output varies with wind speed

$$P_{out} = \frac{1}{2} * C_p * \rho * A * V^3 \qquad (3.1)$$

$\boldsymbol{P_{out}}$ is output power, $\boldsymbol{C_p}$ is power coefficient, $\boldsymbol{\rho}$ is air density, $\boldsymbol{A}$ is swept area by the rotor blades and $\boldsymbol{V}$ is wind velocity. [10].

Power coefficient and power output are dependent on the wind speed [10].

The following figure 2.3. is the characteristics curve of the wind turbine and that exhibits wind turbine power output variation with wind speed.

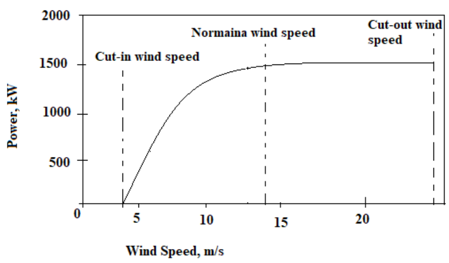

Figure 2.3. Characteristic curve of a typical wind turbine [11]

The wind turbine's characteristic curve, which shows how power output varies with

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wind speed, is illustrated in the above figure. However, given the characteristics curve of any wind turbine, particular attention should be paid to the following three parameters:

Cut-in Wind speed: Is the speed at which the turbine initially rotates and generate power and is normally between 3 and 5 m/s but can vary based on the design of the turbine.

Cut-Out Wind speed or (Cut-off Wind speed): it is the peak wind speed at which turbine must be shut down in order to prevent damage to the equipment. For the majority of wind turbine, the cut off speed is 25m/s [12] [13].

Nominal or Rated Wind Speed: is the lowest wind speed that allows the turbine to run as efficiently as possible. This is equivalent to the generator's rated electrical power output, that it is capable of handling. The estimated speed is normally around 15 m/s [12] [14].

3. Storage Battery

A battery energy storage system makes it simple to collect energy and store it for later use, such as a backup for peak demand or to power off-grid applications. Two major battery types used in hybrid systems are Nickel-cadmium and lead-acid batteries. Due to its low energy efficiency, highest cost as well as limited maximum operating temperature, nickel-cadmium batteries are only used in few systems. Therefore, in hybrid systems, lead-acid batteries are mostly used as energy storage to store excess energy, control system voltage, and provide load in the case of insufficient solar or wind energy due to its highly efficient technology and maintenance-free [15] [16]. There are several capacities of the nominal voltage available, including terminal voltages of 2 V, 6 V, 1 V, and 24 V. The depth of discharge, which measures how much of a battery's energy storage capacity is used at once, has an impact on its lifespan.

The battery capacity needed to meet the entire load demand can be calculated with the help of the following elements:

- E_L: Total Energy Demand [Wh]
- η_B: Battery Efficiency [%]
- (DOD) max: Maximum Depth of Discharge
- V_B: Nominal Battery Voltage [V]
- S_D: Days of Autonomy [days]
- T_{cf}: Temperature correction factor

4. PV-WIND HYBRID POWER SYSTEM CONFIGURATION

Two different energy sources are combined in a hybrid energy system to provide electricity to the load. In other words, it may be said that "A hybrid energy system is one that is created or designed to extract power by utilizing two energy sources.

For regions where grid extension requires significant financial investment and for physically remote locations where power transmission from centralized utilities is challenging, like in the case of Rwanda, it is an acceptable way of providing electricity from locally accessible energy sources The use of hybrid energy systems is reliable, efficient, economical and efficient. In the suggested system, power is produced using solar and wind energy.

As our case study illustrates, the solar panels and wind turbine are utilized to generate power in a solar wind hybrid system with limited solar and wind resources. The block design of this system is displayed in figure 4.1.

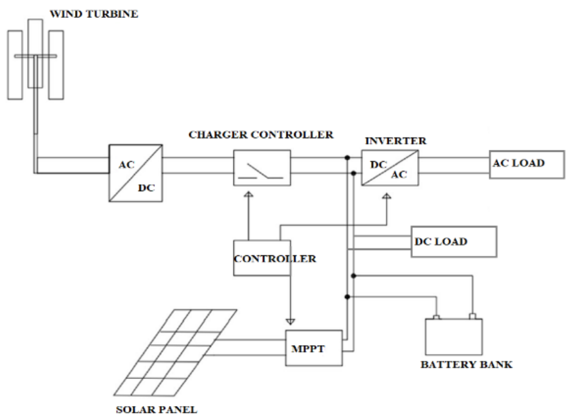

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Figure 4.1. Block diagram of solar wind hybrid system [17]

5. METHODOLOGY

Obtaining wind and solar data from the chosen village is one of the research methods used to accomplish our goals. The data collected in this study showed that Nyamagabe District in Rwanda offers the best conditions for wind-solar hybrid systems due to its strongest wind. Nyamagabe District's wind recorded 7.6 m/s wind speed and the horizontal solar radiation was 7.54 kWh/m^2/day.

Village load profile, components characteristics and cost estimation are other data which were used to design this system. The following research methodology was used to meet our goals:

- Getting the data on solar and wind power from different organizations.
- Identifying the load profile of the village.
- Evaluating characteristics of the components to obtain the input parameters required by our software MATLAB for the purpose of simulating and modeling the system for the selected village.

5.1. VILLAGE LOAD PROFILE

The electric load taken into account at this time is intended to meet the needs of 300 households, which together make up a maximum of 1500 people at the chosen site. In the scenario of a rural village model with 300 households, in addition to the home appliances that require an electric load supply, the following

5.2. TOTAL LOAD DEMAND OF SELECTED VILLAGE

The system is first simulated using only solar and wind energy, and the effectiveness of each system is assessed. Thereafter the effectiveness of the hybrid system is assessed. The following institutions

are present: 10 shops, one school that has 18 rooms and Cell office

Table 5.1. Total demand of selected Village

Item	Total Power (W)	Total Energy (Wh)
Household Load	134660	341440
School Load	9060	12210
Cell Building Load	425	170
Commercial Load	20130	25080
TOTAL	**164275**	**378900**

6. RESULTS AND DISCUSSIONS

6.1. MODELING AND OPTIMIZATION

The optimization model design process for selecting the optimal choice for sizing the hybrid system was carried out using MATLAB simulation. The various outcomes are presented and contemplated.

6.2. HYBRID ENERGY SYSTEM CONFIGURATION

A **164275** W Solar –Wind hybrid system is modelled. Solar power system will produce **289,915Wh** and wind turbine system will produce **88,985 Wh.** The specifications for the wind turbine and solar PV system are given in Tables 6.1 and 6.2, respectively. The wind and solar PV subsystems are shown in Figure 6.1 and 6.5, respectively.

6.2.1. WIND SYSTEM

Table 6.1. Parameters of Wind turbine

Parameters	**Blade Diameter**	**Number of Blades**	**Rated Wind speed**	**Cut-in speed**	**Cut-out speed**
Rating	8.4 m	3	10m/s	2.5 m/s	25 m/s

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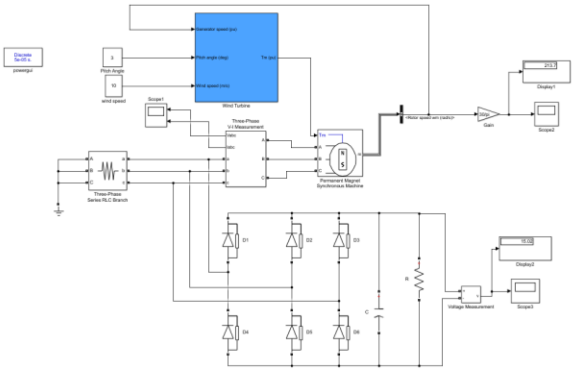

Figure 6.1. Simulink diagram of wind turbine subsystem.

Figure 6.2 shows the Simulation waveform of output power characteristics for various speed wind turbine.

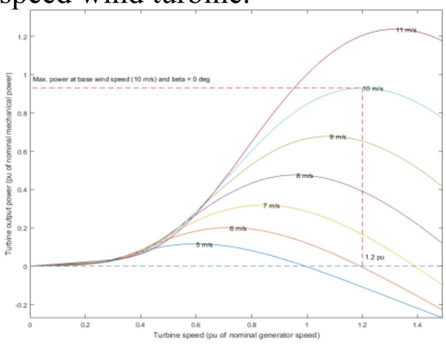

Figure 6.2. Wind turbine Power Characteristics

Figure 6.3 shows the AC voltages of wind energy system and Figure 6.4 shows the DC output voltage of wind energy system respectively

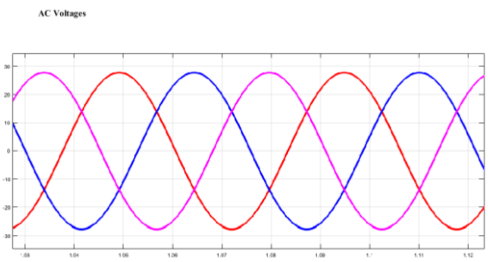

Figure 6.3. AC voltages of wind Turbine

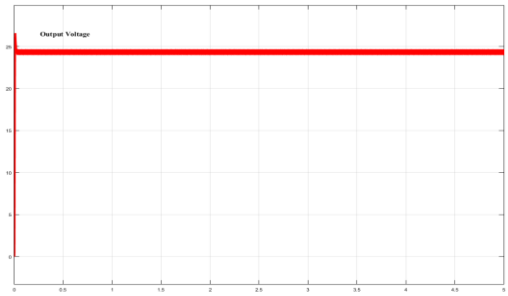

Figure 6.4. Output voltage of wind energy system

6.2.2. SOLAR PV SYSTEM

MATLAB/SIMULINK was used to model and simulate a solar PV system

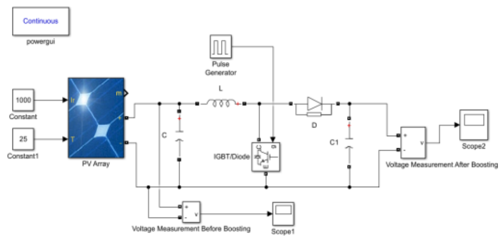

Figure 6.5. Solar PV subsystem Simulation diagram

Table 6.2. Parameters of Photovoltaic Module

Maximum Power	Maximum Voltage	Temperature Coefficient
400 W	37 V	25ºC

Under various solar temperatures and irradiations, the solar photovoltaic module produces the DC voltage. As illustrated in figure 6.6, the energy produced by the modules is not constant; rather, it varies depending on the temperature and the intensity of the sun's photovoltaic rays.

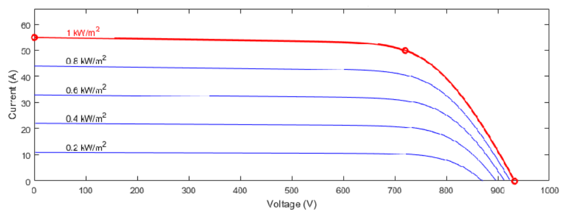

Figure 6.6. Voltage vs. Current characteristics

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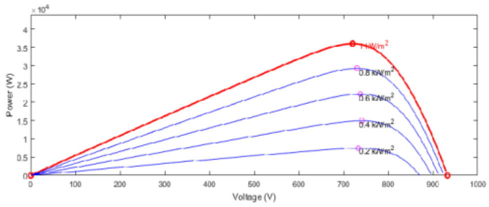

Figure 6.7. Power Vs. Voltage characteristics

The below figure shows the output voltage of Photovoltaic System at 1000 W/m^2 before boosting the voltage. In atmosphere, temperature is not constant. It is varying from morning to evening right. In afternoon time, only we are getting the maximum power but in the morning time and evening time, we are getting the low power right but any time we need to give the load to constant supply for 24 hours.

Therefore, we need to boost up the voltage, to increase the voltage whenever you are not getting the much voltage from solar panel due to cloud it is or rain time. Here, connect the boost converter to meet the load.

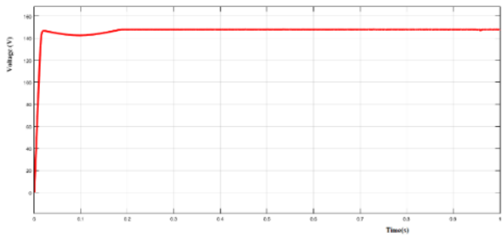

Figure 6.8. Output voltage of Photovoltaic System before boosting

Output voltage of Photovoltaic System at 1000 W/m^2 after boosting the PV array output voltage is shown in the figure 6.9

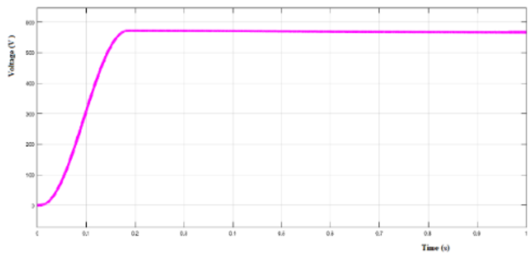

Figure 6.9. Output voltage of Photovoltaic System after boosting

The Voltage Vs Current and voltage-power output characteristics of a Photovoltaic module at irradiation G = 1 kW/m^2, 0.8 kW/m^2, 0.6 kW/m^2, 0.4 kW/m^2, 0.2 kW/m^2 and temperature 25ºc is shown in fig 6.6 and 6.7. It is observed that the output voltage and output current of PV systems are mostly depending on variations in temperature and irradiation right.

6.2.2.1. MAXIMUM POWER POINT TRACKING (MPPT)

The main idea behind MPPT is to operate PV modules at the most effective voltage (maximum
power point) in order to get the most power out of them. That is to say: MPPT evaluates the output of the PV module, compares it to the battery voltage, and determines the best power the PV module can provide to charge the battery.

It then converts that power to the optimum voltage to allow the battery to receive the maximum amount of current.

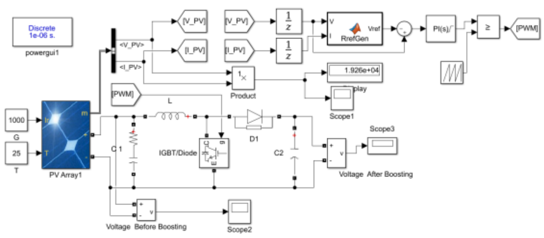

Figure 6.10. Maximum Power Point Tracking (MPPT) Using boost Converter

The output Power of PV systems is mostly depending on variations in temperature and irradiation right.

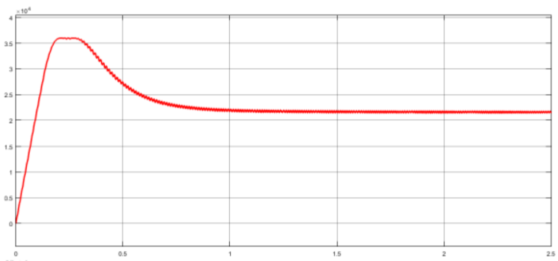

Figure 6.11. MPP for 1000 radiation

6.2.3. HYBRID SYSTEM

To satisfy the demand in this situation, both a wind and solar PV system is employed. Their Output Voltages are combined with a universal bridge to get the output Voltage of 230V.

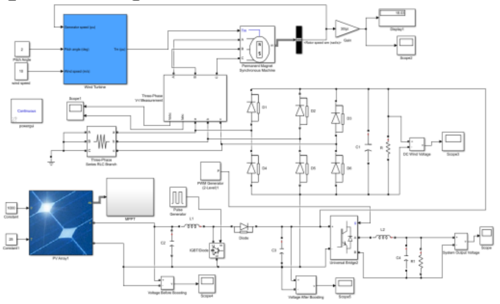

Figure 6.12. MATLAB/SIMULINK model of Hybrid system

The DC output Voltage is converted to AC using Universal Bridge, which works as Inverter and Passive filter

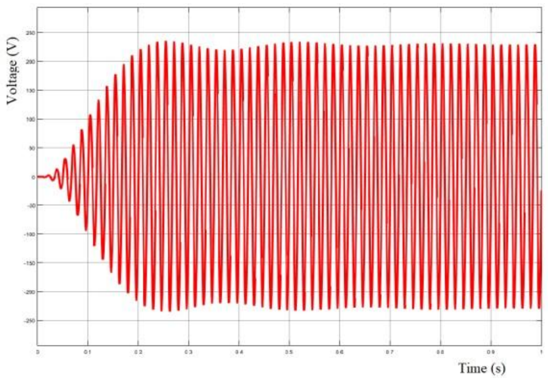

Figure 6.13. Time vs Output voltage of wind (10 m/s) and Solar PV (1000W/m^2)

CONCLUSION

The design of a solar-wind hybrid power system for a community of 300 households in the remote area of Nyamagabe district has been devoted in this thesis study. Nyamagabe District's wind recorded 7.6 m/s wind speed at a height of 35 m, while the horizontal solar radiation was 7.54 kWh/m2/day. These data were examined using MATLAB SIMULINK, and the outcome shows that it is feasible to take advantage of wind and solar energy potentials for producing electricity as a hybrid system.

By paying close attention to the country's electricity shortage, many aspects of life for the community living in rural areas, which continues to be important for many Rwandans, will be improved such as education, commercial activities. The system is also friendly to the environment.

Every Rwandan must have access to inexpensive electricity, according to the Government's strategy; this crucial factor has to be taken into account. Government support is highly needed to establish this power generating system.

alternatives and that it is more cost-effective and appealing than grid electricity.

For the electrification of the chosen rural community, provided that local trained personnel are employed for maintaining the system. Under the latter condition, the cost of energy for the hybrid system will be significantly lower than that from the national grid. Finally, I could say that this hybrid power system is a superior alternative to currently available

Every Rwandan must have access to inexpensive electricity, according to the Government's strategy; this crucial factor has to be taken into account. Government support is highly needed to establish this power generating system.

Finally, I could say that this hybrid power system is a superior alternative to currently available alternatives and that it is more cost-effective and appealing than grid electricity. For the electrification of the chosen rural community, provided that local trained personnel are employed for maintaining the system. Under the latter condition, the cost of energy for the hybrid system will be significantly lower than that from the national grid.

REFERENCES

[1] REG, "RWANDA AND JAPAN CELEBRATE COOPERATION IN ENERGY SECTOR DEVELOPMENT," *Newsletter,* January- March, 2023.

[2] T. Abrar, M. Shabbir and O. Siddiqui, WIND & SOLAR RENEWABLE ENERGY, 2016.

[3] P. C. S. p. Kousik Ghosh, Solar and Wind Hybrid Power Generation.

[4] C. M. YANDIOLA, Feasibility Analysis of the use of the use of Hybrid Solar PV-Wind Power Systems for Grid integrated Mini-grids in India.

[5] "https://ccsuniversity.ac.in/bridge-library/pdf/ME_1.SOLAR%20CELL.pdf," [Online].

[6] N. A. B. Berino Francisco Silinto, Feasibility Study of Solar-Wind Hybrid Power System for Rural Electrification at the Estatuene Locality in Mozambique, 2015.

[7] N. S. a. A. Goswami, "Study of P-V and I-V Characteristics of Solar Cell in MATLAB/ Simulink," 2018.

[8] A. L. a. S. Hegedus, Handbook of Photovoltaic Scienceand Engineering.

[9] F. A. A. M. O. E.E. Iheonu, Wind Resources Variations over selected sites in the West African sub-region. Nigerian J. Renewable Energy,, 2002.

[10] S.Mathew, Wind Energy: Fundementals, Resource Analysis and Economcs, 2006.

[11] B. Univeristy, "Mechanical Engineering Department," *Wind Turbines,* 2010.

[12] P.Jain, Wind Energy EEngineering, 2011.

[13] Electropaedia, "https://www.mpoweruk.com Wind Power," [Online].

[14] -J. a. J. H, Introduction to Wind Energy System: Basics, Technology and Operation, Springer, 2009.

[15] D. Gielen, Electricity Storage and Renewables for Island Power, A Guide for Decision Makers, 2012.

[16] M. M. Mahmoud, On the Storage Batteries Used in Solar Electric Power Systems and Development of an Algorithm for Determining their Ampere-Hour Capacity, 2009.

[17] M. E. D. A. (MEDA), "Small Wind Energy and Hybrid Systems Programme," 2023.