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Design of International Airport Hybrid Renewable Energy System

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ABSTRACT

This paper presents the design and simulation of a hybrid renewable energy system utilizing solar and wind energy sources with a backup generator. The demand for reliable electric energy in support of investments in large social and economic development activities such as airport operations has been an agenda worldwide. In Tanzania, Mwanza International Airport (MIA) expects to consume about 18 MVA of electric power annually to support its operations for the next 25 years. About 78-80% of the world's commercial energy comes from fossil fuels. Non-renewable fuels and other negative effects contribute to global warming through greenhouse gas emissions and carbon dioxide emissions. Additionally, most centralized conventional power generation methods require transmission systems, adding complexity and poor power quality. Therefore, the proposal to use a mixed-coupled hybrid renewable energy source to power the airport is necessary. The energy mix considered is solar photovoltaic (PV), wind, diesel generator and a battery. There is an average solar irradiation of 5.38 kWh/m^2 and a wind speed average of 4.20 m/s that could be converted to electricity by installing a 10-kW wind turbine (this is enough to generate power for MIA). The diesel generator and the battery designed at 140 kVA and 400 Ah, respectively, take the intermittency. The project will be in operation for 25 years; hence its costs are reasonable, and the justification is the potentiality of harvesting that estimated energy output of 18 MVA, which will meet the load for MIA. Some mathematical computations were performed, and, in the end, simulation results displayed different techno-economic Hybrid Renewable Energy Source (HRSE) configurations. The selected system's complete design would include a 78.48 kW PV system comprising 314 pieces of 200 W poly-crystalline modules, 608 batteries of 83.4 Ah, 12 V rating, 140 kVA diesel generator, and 41.64 kVA bidirectional converter. The net present cost of the selected design is US$357,780.8, the energy cost is 0.93US$/kW, and the minimum renewable fraction is 40.2%.

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INTRODUCTION

The demand for reliable electric energy in support of investments in large social and economic development activities has been an agenda worldwide. Generally, governments and private sectors have used conventional methods for generating electrical power. About 78-80% of the world's commercial energy comes from fossil fuels (EESI, 2021). Non-renewable fuels such as petroleum, coal and natural gas have been used to generate electric power with drawbacks such as discharge and dielectric losses, heating effects of the conductor over a long distance and negative effects on the environment through carbon dioxide emissions and therefore, contributing to global warming through the greenhouse effect. Additionally, most of these centralized conventional generation methods require transmission systems, which add complexity to the system and have often resulted in systems that look unplanned and have poor power quality (Sekhar et al., 2016). This situation brought an opportunity and innovative concept of utilizing renewable energy for efficient, accessible, environmentally friendly and affordable energy supply through technological revolutions (Justo & Mushi, 2020). Various studies reveal that deploying Renewable Energy Sources (RES) can be a good alternative to energy supply in the long term. The off-grid hybrid power generation is a feasible option for developing renewable energy systems (Minja & Mushi, 2021, 2022).

Renewable energy sources such as solar photovoltaic (PV), wind, and geothermal energy have several benefits, including reducing dependence on imported fuels and creating jobs in manufacturing and installation processes. The collection and use processes of the resources are safer than that of non-renewable sources. As solar and wind energy conversion costs drop, the stage appears set for a strong expansion of renewable power production in the decades to come, underlined by African countries' pronounced policy focus on hybrid renewable power mixes for increasing electricity access (Sterl et al., 2019).

Since her independence, the demand for electrical energy has kept increasing in Tanzania to industrialization, urbanization and population growth (Irechukwu & Mushi, 2020; Mushi, 2022). The government policies are currently towards the revival and enhancement of transport infrastructure, especially airport transport, as well as the growth of the industrial sector. However, to realize the proposed power generation, the use of Reliable Electrical Power (REP) is among the prime requirements. A hybrid renewable energy system can be in stand-alone or grid-connected modes. A stand-alone system must have large storage to handle the load while in a grid-connected mode, the storage can be small, and the deficient power acquired is supplied by the grid (Ferdous et al., 2016). The grid-connected mode must have a power electronic controller for load sharing; voltage, harmonic, and frequency control for power distribution.

Airport systems have high electrical energy demand for lighting, cooling (air conditioning), lift, security checking systems, baggage handling systems and power at gates (ICAO, 2016). Airport airside needs electricity for airfield grounding lighting, auxiliary power units, passenger Board Bridge, aircraft ground energy systems, ground-handling equipment, firefighting services and hangar. The existing power supply for Mwanza International Airport (MIA) is a three-phase underground service line supplied by Tanzania Electrical Supply Company Limited (TANESCO) at 11 kV (Minja & Mushi, 2021, 2022).

The power is terminated at switchgear with single point metering, which is distributed to various services after stepping down to 415 V through power transformers and LV distribution panels. In case of power disruption from TANESCO, power supply through the Diesel Generator (DG) set is provided with Auto Transfer Switch (ATS) switchgear for the operation of essential services. The DG provides power within 15 seconds of mains power failure from TANESCO. The current total load of MIA is 350 kVA.

METHODS AND MATERIALS

Design procedures of the HRES

Mixed Hybrid Renewable Energy System (MCHRES) can be designed based on different technical topologies to harvest the available renewable and non-renewable energy potentials to meet the required load (Fungo et al., 2021; Marcel et al., 2021; Sterl et al., 2019). In this paper, the MCHRES shown in Figure 1 was designed. The system consists of two buses such as AC and DC buses. The AC sources, such as wind and diesel generators, feed to the AC bus while the battery bank and solar PV systems are connected to the DC bus with a bidirectional converter linking the two buses. All loads are assumed to be AC loads connected to the AC bus. This system has higher loads than the DC loads (Juma et al., 2021a; Juma et al., 2021b). Compared with other MCHRES design topologies, mixed-coupled power system design maximizes diesel efficiency and has the possibility of a decrease in diesel fuel utilisation and battery capacity (Kaabeche et al., 2010). It also offers optimal power generation and controllability (Bahta, 2013).

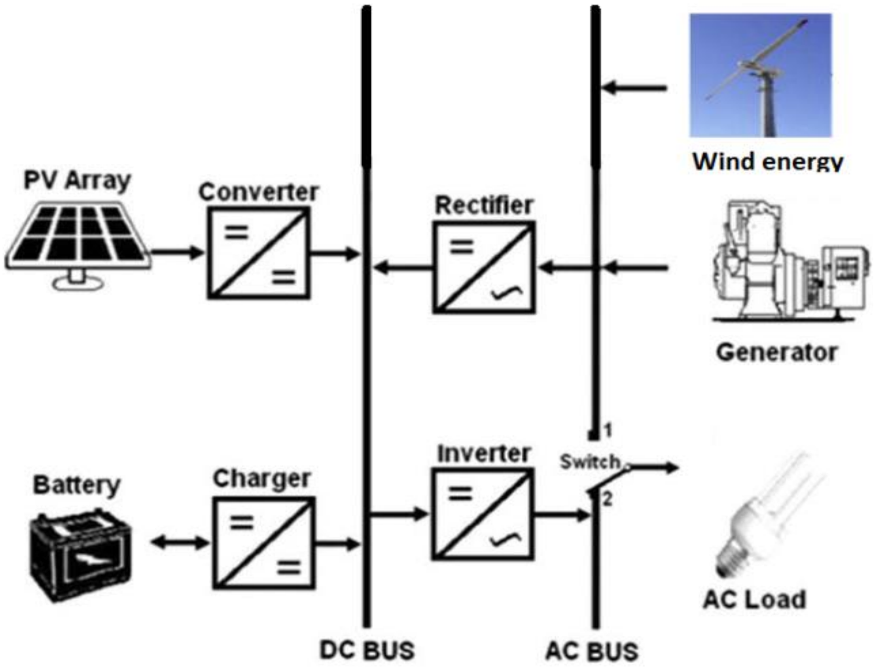

Figure 1: Proposed HRES topology for MIA.

Estimation of electricity generation at Mwanza International Airport (MIA)

MIA is approximately 10 km outside the city of Mwanza; depicted by the map of Figure 2. It is at latitude -2° 26' 24.08" S and longitude 32° 55' 34.55" E; and an elevation of 1151 m above sea level. The airport handles both domestic and international flights. Due to the high electricity tariff of Tanzania (Kihwele et al., 2012), there is a need to develop alternative cheaper energy sources for powering MIA. One of the options is to use renewable energy sources such as solar PV and wind energy conversion systems. Each year, the solar energy received on the earth’s surface is more than enough to supply the world's energy requirement (Chiras, 2010). Therefore, for the optimum angle, one can use solar radiation databases to estimate the solar PV energy potential at MIA depicted in Figure 3. Then, one can determine the wind speed data for the site from 10 m to 20 m height from the ground of MIA. The wind energy potential at the airport was estimated using data provided by Tanzania Meteorological Authority (TMA), as depicted in Figure 4.

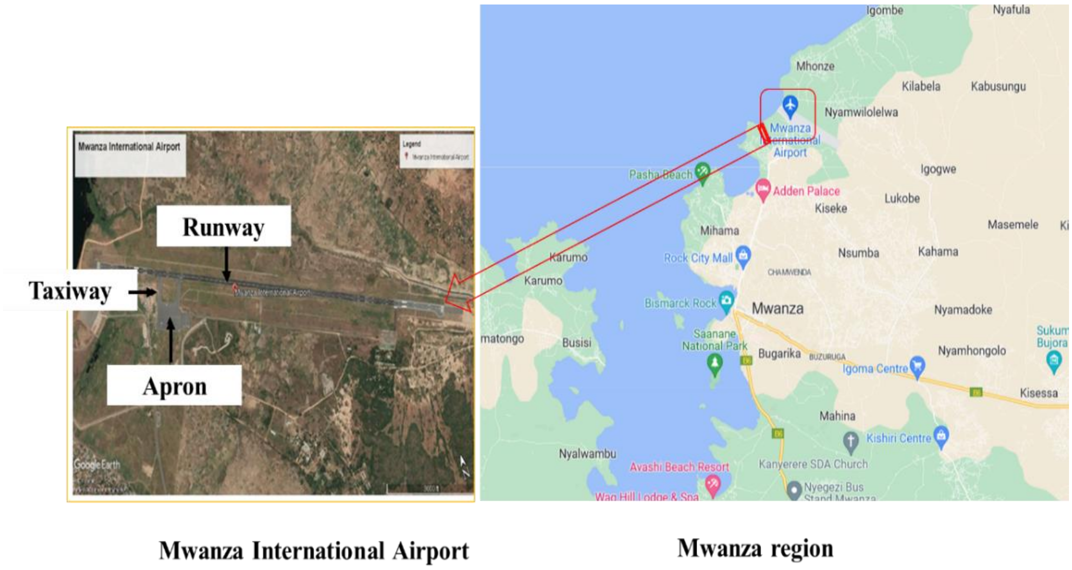

Figure 2: Map showing the location of MIA infrastructures (google maps, 2023)

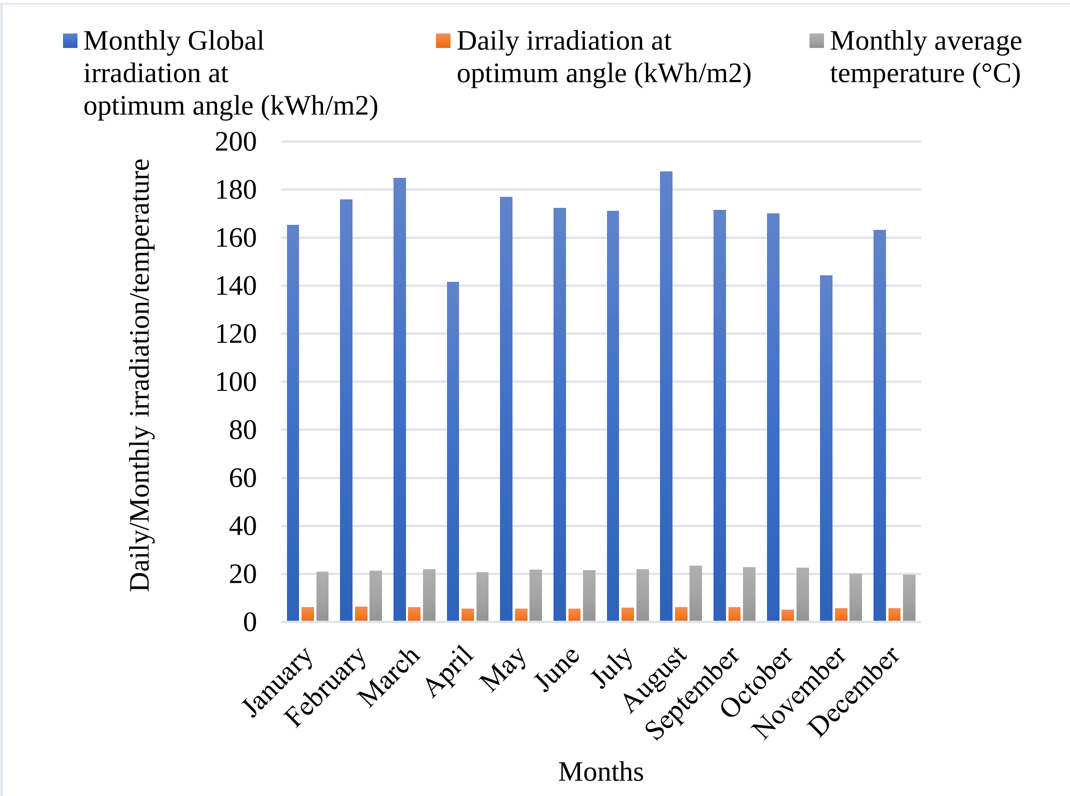

Figure 3: Daily and monthly solar irradiations and temperature in Mwanza.

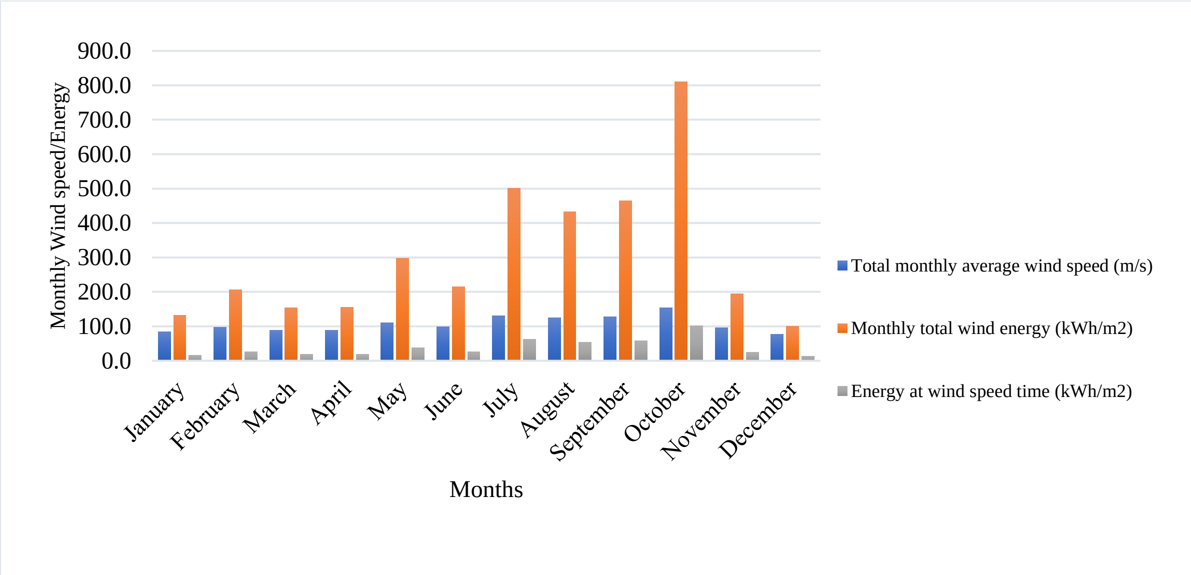

Figure 4: Wind energy potential of the MIA site.

Mathematical model of solar PV system

Designing an efficient solar PV system to enhance its performance for maximum power production is very significant. A solar PV array can be modelled using different approaches. Several parameter data are required for modelling solar PV system, such as incident solar radiation, areal ambient temperature, and manufacturer's PV module specifications. Wang (2006) explained that PV output power could be determined by Equation (1).

$P_{PV} = \eta_g N A_m G_t$ $P_{pv} = \eta_g N A_m G_t$ (1)

where P_{PV} P_{pv} is the solar PV power generator output [W], η_g η_g is the solar PV generator efficiency [%], A_m A_m is the area of a single module [m^2], G_t is the global radiation [W/m^2], and N is the number of solar modules assembled in the system. The solar PV generator efficiency can be presented in by Equation (2).

$\eta_g = \eta_r \eta_{pt}\left[1-\beta_t\left(T_c - T_r\right)\right]$ $\eta_g = \eta_r \eta_{pt}[1-\beta_t(T_c\text{-}T_r)]$ (2)

where η_r is reference efficiency [%], η_{pt} is solar tracking system efficiency [%], T_c is the PV cell temperature [K], T_r is the PV cell reference temperature [K], and β_t is the temperature coefficient of efficiency ranging from 0.004 to 0.006/°C for silicon cells.

$T_c = T_a + G_t\left(\frac{\alpha\tau}{U_1}\right)$ $T_c = T_a + G_t\left(\frac{\alpha\tau}{U_1}\right)$ (3)

$\frac{\alpha\tau}{U_1} = \frac{NOCT - 20}{800}$ $\frac{\alpha\tau}{U_1} = \frac{\text{NOCT-20}}{800}$ (4)

Further, T_a the ambient site temperature [K] α are photovoltaic transmittance and absorptance coefficients, respectively. These parameters η_{pt}, β_t, and $NOCT$ are parameters that depend on module type and can be obtained from the module manufacturer's datasheet (Equations (3) and (4)).

Mathematical model of wind system

The theoretical power available in the wind per 1 m^2 of rotor swept area can be mathematically expressed by Equation (5).

$P = \frac{1}{2}\rho V^3$ $P = \frac{1}{2}\rho V^3$ (5)

The power density available in the wind is P [W/m^{2}m2], wind speed is V [m/s], and

ρ is the air density [kg/m^3]. Since air temperature and humidity are variable, the air density varies with altitude. Taking air density of 1.225 kg/m^3 as a reference, the specific air density of the site can be determined by Equation (6) as given by (Bahta, 2013).

$$\rho = \rho_0 - 1.194 \times 10^{-4} H_m \quad \rho = \rho_0\text{-}1.194 \times 10^{\text{-}4}\mathrm{H_m} \qquad (6)$$

The H_m is site elevation [m], and ρ_0 is the air density at sea level [1.225 kg/m^3]. The electrical power of the wind turbine is expressed mathematically by Equation (7).

$$P_{el} = \frac{1}{2}\rho V^3 C_p \eta_g \eta_m \quad \mathrm{P_{el}} = \frac{1}{2}\rho \mathrm{V^3 C_p} \eta_g \eta_m \qquad (7)$$

where P_{el} is the wind turbine electrical power density [kW/m^2], η_g is the electrical generator efficiency [%], η_m is the mechanical gearbox efficiency [%], and C_p is the power coefficient of the wind turbine, given as 0.4 and 0.5 for two blades rotor and between 0.2 to 0.4 for more blades as well as low-speed turbines (Wang, 2006).

Mathematical model of battery bank system

The total capacity of the battery capable of supplying the full load demand can be determined using Equation (8) (Kaabeche et al., 2010).

$$C_B = \frac{E_L S_D}{V_B DOD_{\max} T_{cf} \eta_B} \quad \mathrm{C_B} = \frac{\mathrm{E_L S_D}}{\mathrm{V_B} \times \mathrm{DOD_{max}} \times \mathrm{T_{cf}} \times \eta_\mathrm{B}} \qquad (8)$$

where C_B $\mathrm{C_B}$ is the capacity of battery [Ah], E_L $\mathrm{E_L}$ is the electrical load [Wh], S_D $\mathrm{S_D}$ is the battery autonomy [days], V_B is the battery voltage [V], $DOD_{\max}$ $(\mathrm{DOD})_{\max}$ is the maximum allowed depth of discharge of the battery, T_{cf} is the temperature correction factor, and η_B η_B is the efficiency of battery [%]. The autonomy period of a battery bank is the ratio of battery bank size to the load demand (Equation (9)) as per (Dufo-López et al., 2021; Khan et al., 2021).

$$S_D = \frac{N_B V_{nom} Q_{nom} \left(1 - q_{\min}/100\right)}{I_{prim-ave}\left(\dfrac{1000\ \text{Wh}}{\text{kWh}}\right)} \left(\frac{24\ \text{h}}{\text{day}}\right)$$

$$\mathrm{S_D} = \frac{\mathrm{N_{batt}} \times \mathrm{V_{nom}} \times \mathrm{Q_{nom}} \times (1\text{-}\mathrm{q_{min/100}}) \times (\frac{24\text{hr}}{\text{day}})}{\mathrm{I_{prim,ave}} \times (1000\frac{\text{Wh}}{\text{kWh}})} \qquad (9)$$

where N_B $\mathrm{N_{batt}}$ is the number of batteries, V_{nom} $\mathrm{V_{nom}}$ is the single battery nominal voltage [V], Q_{nom} $\mathrm{Q_{nom}}$ is the single battery nominal capacity [Ah], $q_{\min}$ is the battery bank minimum state of charge [%], and $I_{prim-ave}$ $\mathrm{I_{prim,ave}}$ is the average primary electrical load [kWh/day].

Mathematical model of Converters

The converters in this project were inverter and rectifier. The mathematical models of these converters are as given by Johannesen et al. (2021), Josue & Mushi (2022) and Kumar Lal et al. (2011) as shown by Equations (10) and (11).

$$E_{PVG-IN}(t) = \eta_{INV} E_{PVG}(t) \quad \mathrm{E_{PVG\text{-}IN}(t)} = \eta_\mathrm{INV}\mathrm{E_{PVG}(t)} \qquad (10)$$

$$E_{BAT-INV}(t) = \frac{E_{BAT}(t-1) - E_{LOAD}(t)}{\eta_{INV}\eta_{DCHG}}$$

$$\mathrm{E_{BAT\text{-}INV}(t)} = \left[\frac{\mathrm{E_{BAT}(t\text{-}1)}\text{-}\mathrm{E_{LOAD}(t)}}{\eta_\mathrm{INV}\eta_\mathrm{DCHG}}\right] \qquad (11)$$

where $E_{PVG-INV}(t)$ $\mathrm{E_{PVG\text{-}IN}(t)}$ is the energy output from inverter [kWh], $E_{PVG}(t)$ $\mathrm{E_{PVG}(t)}$ is the energy output from solar PV generator [kWh], η_{INV} is the inverter efficiency [%], $E_{BAT-INV}(t)$ is the energy output from battery [kWh], $E_{LOAD}(t)$ is the energy consumed by the load [kWh], η_{DCHG} is the battery discharging efficiency, and $E_{BAT}(t-1)$ is energy stored in battery until time step $t-1$ [kWh]. The rectifier is the converter used to convert the AC power from the wind generator and diesel generator to DC for battery charging. Its mathematical expression is as shown by Equation (12) (Khamharnphol et al., 2023).

$$E_{REC-OUT}(t) = \left(E_{WEG}(t) + E_{DEG}(t) - E_{load}(t)\right)\eta_{REC} \quad (12)$$

Where $E_{REC-OUT}(t)$ is the energy output per hour from the rectifier [kWh], η_{REC} is the rectifier efficiency, $E_{WEG}(t)$ is the energy generated by wind generators [kWh], $E_{DEG}(t)$ is the energy generated by diesel generator [kWh], and $E_{load}(t)$ is the hourly energy consumed by the load [kWh].

Mathematical model of backup diesel generator

The efficiency equation of the power generator when the unit of fuel flow is in litres is given by Equation (13).

$$\eta_{gen} = \frac{3600 P_{gen}}{\rho_{fuel}\left(F_0 Y_{gen} + F_1 P_{gen}\right) L_{HVf}} \quad (13)$$

where η_{gen} is the generator efficiency, P_{gen} is the diesel generator electrical output [kW], ρ_{fuel} is the fuel density [kg/m^3], F_0 is the fuel curve intercept coefficient [units/h/kW], Y_{gen} is the fuel curve slope [units/h/kW], F_1 is the rated capacity of diesel generator [kW], L_{HVf} is the lower heating value [MJ/kg], and 1 kWh = 3.6 MJ.

Component size specifications and cost

The main purpose of this project was to design an optimum HRES power system topology that would meet the load demand of 18 MVA at MIA with minimum Net Present Cost (NPC) and Cost of Energy (COE). Table 1 summarizes the specifications of components in the HRES schemes. Cost data were obtained after a survey from different manufacturers and sellers within the country and online.

Table 1: Components cost data and size specifications for MIA

Component	Size or capacity/Unit	Capital cost (TZS)/Unit	O & M cost (TZS/year)	Replacement cost (% of the capital cost)	Component life (years)
Solar PV module (poly-crystalline)	200 W	200,000	20,000	70	25
Wind turbine	10 kW	5,500,000	200,000	70	20
Battery	400 Ah, 12 V	1,020,000	20,000	70	15
Diesel generator	140 kVA	41,742,000	2,092,387	100	15
Converter	41.64 kVA	4,400,000	50,000	70	15

SIMULATIONS

The simulation was carried out using the Hybrid Optimization of Multiple Energy Resources (HOMER) Pro software tool. HOMER simulated different configurations of the HRES system and displayed the feasible power schemes for further detailed analysis and selection of the most optimal system. The simulation time is hugely affected by the number of parameters involved in the design. There were six (6) parameters with 53,012 simulations in the design of the HRES. The optimum system was recommended for the HRES scheme with less NPC, less COE, higher renewable fraction, less capacity shortage, smaller excess electricity, and minimum fuel consumption. Table 2 depicts the simulation results displaying different HRES schemes, which are termed as follows:

(i) PV-Generator-Battery Bank (Scheme A);

(ii) PV-Wind-Generator-Battery Bank (Scheme B);

(iii) PV-Wind-Battery Bank (Scheme C); and

(iv) PV-Battery Bank (Scheme D).

The HOMER software tool permits modelling taking account of future load demand dynamics and generation resource fluctuations. Sensitivity parameters chosen when modelling HRES tells how sensitive the power system is prior to the input variables. These are load, maximum capacity shortage, minimum renewable fraction and diesel price. The advantage of sensitivity variables in modelling is to analyse the uncertainty about the power system. Many sensitivity variables take more HOMER computational time. Table 2 depicts the sensitivity variables used in the simulation.

Table 2: Sensitivity variables used for HOMER simulations

Load	Maximum capacity shortage	Minimum renewable fraction [%]	Diesel price [US$/litre]
60 kWh/day, 115.34 kW peak	0, 5, 8, 10	40, 60	0.86, 0.95, 0.97, 1.01

Note 1: The exchange rate is US$1 = TZS 2304.6541 on 11th August 2022 (BOT, 2022).

Note 2: Maximum capacity shortage is the ratio of the shortfall of the required capacity to the actual operating/generating capacity. This ratio reflects how much the power generation meets the load requirements.

Architecture						Cost				System	
PV (kW)	Wind	Genset (kW)	Battery	Conv (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
78.5		140	608	41.6	LF	$0.932	$357,781	$11,579	$154,835	40.3	4,402
78.5	1	140	608	41.6	LF	$0.936	$359,150	$11,603	$155,783	40.3	4,400
261	1		1,360	141	LF	$1.62	$623,334	$18,217	$304,035	100	0
288			1,328	138	LF	$1.63	$626,659	$18,050	$310,282	100	0

Figure 5: The HOMER simulation results of the four HRES schemes.

Schemes comparisons were performed, keeping the constraint values constant for all system configurations (Figure 5). The best power system was selected with less Net Present Cost (NPC), less Cost of Energy (COE), high renewable fraction, less capacity shortage, and less fuel consumption. The worst constraint cases are the maximum annual capacity shortage and minimum renewable fraction.

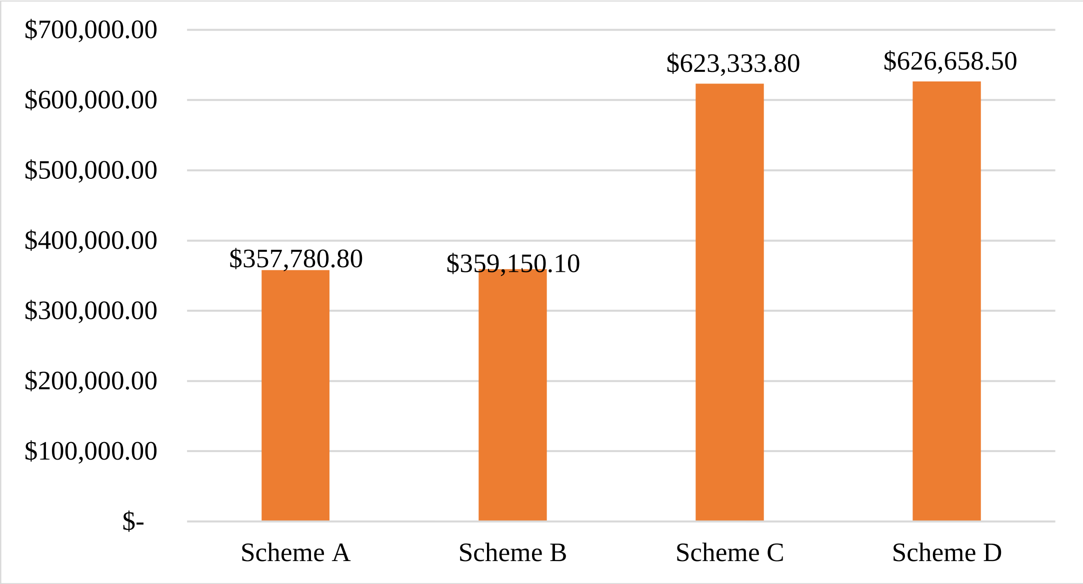

Figure 6: Simulation results based on total NPC for the four hybrid schemes.

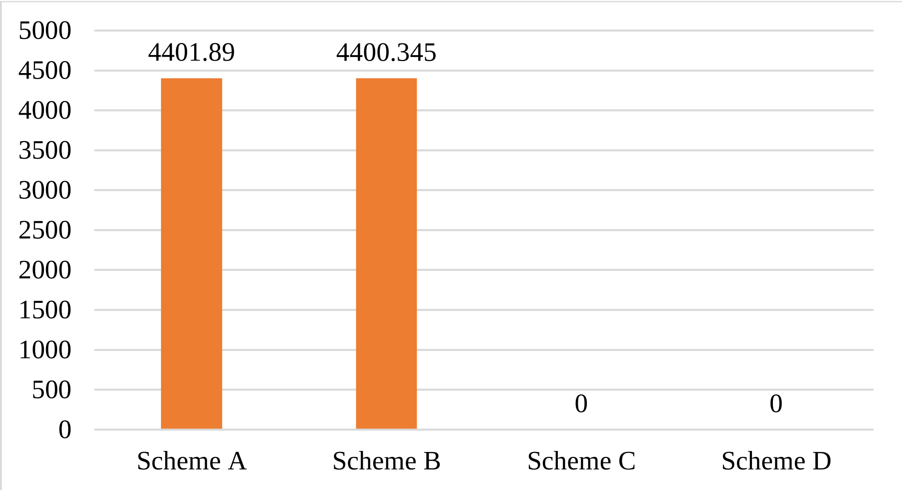

Figure 7: Simulation results based on total diesel consumption for the four hybrid schemes.

Referring to Figures 6 to 9, one realizes which HRES scheme is the winner or technically feasible. Considering NPC and COE, scheme A is the winner. Scheme A comprises the PV system, backup diesel generator and battery bank. The NPC of the scheme was recorded as US$357,780.80 and COE of 0.93 US$/kWh (Figure 6). Scheme A has a minimum renewable fraction of 40.2%. The resulting PV system capacity for Scheme A was 78.48 kW, which means 314 pieces of solar modules of 200 W each, a battery bank of up to 608 batteries of 83.4 Ah each, a backup diesel generator of 140 kVA rating, a bidirectional converter of 41.64 kVA with an operating cost of US$ 11,578.51 per year.

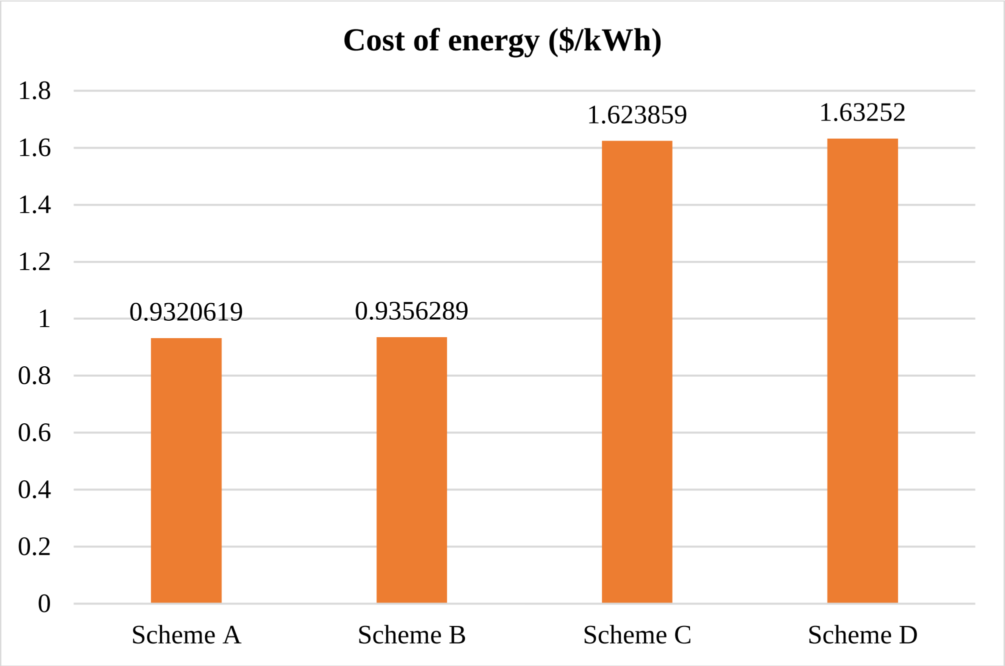

Figure 8: Simulation results based on COE for the four hybrid schemes.

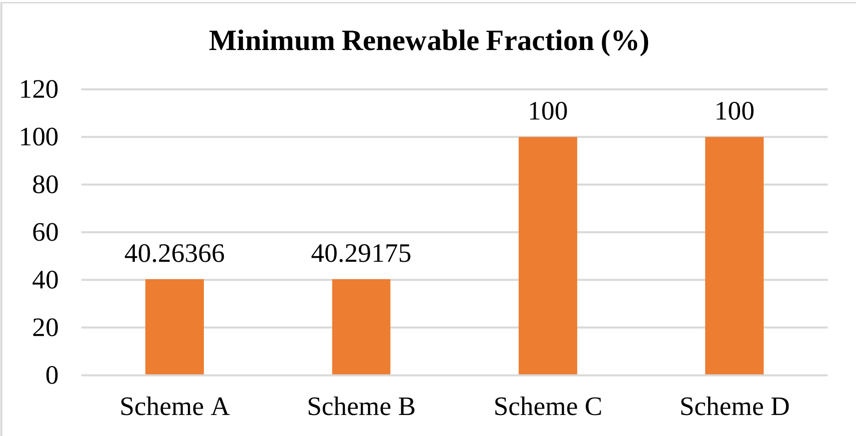

Figure 9: Simulation results based on renewable fractions for the four hybrid schemes.

CONCLUSION AND RECOMMENDATION

In this paper, a hybrid renewable energy source was designed for three new cargo buildings at Mwanza International Airport. The recent renewable energy potential data were obtained from Tanzania Meteorological Authority and the PVGIS web tool. The design was completely off-grid and was designed and simulated using HOMER software. The simulation results displayed different techno-economic HRES configurations. Different configurations were compared based on NPC, COE, minimum renewable fraction and diesel fuel consumption. The system with solar PV, generator and battery bank was selected due to its lower NPC, lower COE, and lower operating cost per year. The complete design of the selected system would include a 78.48 kW PV system comprising 314 pieces of 200 W poly-crystalline modules, 608 batteries of 83.4 Ah, 12V rating, load following dispatch strategy, 140 kVA diesel generator, and 41.64 kVA bidirectional converter. The net present cost of the selected design was US$ 357,780.80; the cost of energy was 0.93 US$/kW; and the minimum renewable fraction of 40.2%.

Some improvements should be made to generate energy efficiently at the minimum possible cost to meet energy demand for the future. Suggestions for future work can be summarized as follows:

- In this research, the efficiency of components was not considered; thus, for optimal feasible design, this parameter could be included in the future.
- Accurate recording and measurement of wind and solar potential of the area should be done.
- The exact kW rating of appliances in the MIA cargo buildings should be studied in detail.
- Accurate load consumption of specific appliances or equipment should be studied.
- Accurate and recent cost data of components should be obtained.
- Considering increasing sensitivity cases for more feasible solutions of the HRES designs.

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