Sustainable Energy Transition in Sub-Saharan Africa: Multi-Objective Optimization for Net-Zero Energy Buildings

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Abstract

Sub-Saharan Africa (SSA) is challenged by an energy crisis characterized by rising demand for electricity, unstable electricity supply and high reliance on fossil fuels. Despite abundant renewable energy resources (RES), the region remains energy insecure, exacerbating socio-economic and environmental challenges. Net-Zero Energy Buildings (NZEBs), which generate as much energy as they consume annually through RES, present a viable solution to reduce fossil fuel dependence, reducing energy costs, and mitigate climate change. This study employs Multi-Objective Genetic Algorithm (MOGA) in MATLAB to optimize NZEB systems, integrating solar PV, wind, battery storage, and hydrogen. Two optimization strategies are considered: minimizing Annual Cost of the System (ACS) and Loss of Power Supply Probability (LPSP), and incorporating Total Energy Transfer (TET) minimization for grid stability. The optimized system increases the renewable energy fraction (REF) by 96.72% and decreases the levelized cost of energy (LCOE) from \$0.24/kWh to \$0.21/kWh, shortening the payback period from 9.29 years to 8.03 years. In addition, it saves more than 1.09 million kg of CO_2 emissions each year and prevents 637,000 m² of deforestation. These findings provide a scalable model for incorporating NZEBs into energy policy in SSA, including strategies for energy-efficient building codes and grid modernization.

Keywords: Net-Zero Energy Buildings (NZEBs), Multi-Objective Genetic Algorithms (MOGA), Grid-connected hybrid renewable energy systems, sustainable energy transition, Sub-Saharan Africa, carbon emissions reduction, land requirement

1. Introduction

SSA is confronted with enormous energy problems which are stifling its socio-economic growth. Over 600 million people are without access to stable sources of electricity, rapid population growth and increased urbanization added pressure on the already immature energy infrastructure of the region ("Africa Energy Outlook 2022," 2022). Despite abundant RES such as solar, wind, and biomass, SSA continues to rely heavily on fossil fuels to meet its energy needs. This dependence exposes local economies to the volatility of global fossil fuel markets and contributes significantly to greenhouse gas emissions, exacerbating the already noticeable impacts of climate change, including increasingly frequent extreme weather events such as droughts and floods (IPCC, 2018). In such a context, sustainable alternative energy production devices for satisfying the increasing demand of electricity are currently in great demand and those which can result from the cleaner energy sources. Although the adoption of NZEBs is potentially a solution to the energy crisis in SSA. NZEBs are expected to generate the same amount of energy they consume each year, from renewable sources such as wind and solar. These buildings not only reduce dependency on fossil fuel sources, but also decrease life-time energy use costs and carbon emissions, thereby playing a role in the global fight against climate change (Banerjee, 2015; Griffith et al., 2020). With the emergence of solar and wind technologies, which have become increasingly cheaper, SSA could be in a position to transition towards a greener and more climate-attentive energy model (IRENA, 2021).

However, despite the promise offered by NZEBs, their uptake in SSA is still low. The region, is also faced with serious challenges to adopting these technologies; some of which include: high cost associated with RES deployment in terms of capital investment, lack of access to finance, immature energy market and weak regulatory framework (Obasanjo, 2018). As such, there is an urgent requirement for case-specific examinations to explore the possibility and merits of NZEB in SSA. The present study we are looking into Kenya with the impressive advancement in RE and hence a typical case for NZEB implementation. The Kenyan government has undertaken various strategies to encourage solar, wind and geothermal energy development, and its enabling policy environment for RE development makes it realizable that NZEBs are achievable (Rotich et al., 2024). The objective of this study is to optimize a HRES for a NZEB in the University of Nairobi (UoN) Chiromo Campus employing MOGA in MATLAB with the view to discern the techno-economic and environmental assessment of the considered HRES, taking into account its

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deforestation and land use impact.

2. Literature Review

SSA is confronted with a significant energy crisis. More than 600 million inhabitants of the region do not have reliable access to electricity according to statistics from the International Energy Agency ("Africa Energy Outlook 2022," 2022), an issue that hinders economic expansion and fuels social disparity. The region is well endowed with RES, but fossil fuels rule the roost. This high reliance compromises local economies to the risks of international energy market fluctuations and is one of several drivers of growing climate change pressures, such as droughts, floods, and other extreme events (IPCC, 2018). In such scenario, there is growing demand for sustainable power product which will serve remedial measures to overcome the challenges and would guarantee uninterrupted energy access in long run by keeping nature friendly environment.

NZEBs have been identified as game changers to SSA's energy challenges. These buildings can generate the amount of energy as they consume on an annual basis by incorporating RES including solar PV and WT (Banerjee, 2015). Therefore, the role of NZEBs is to decrease fossil fuel dependence, lower energy costs and reduce environmental harms caused by traditional methods of producing power. Adoption of the NZEBs in the SSA may have a large potential, since there are unreliable power grids in the region, especially given that in remote areas NZEBs can be more beneficial since they constitute decentralized sources (Griffith et al., 2020). Additionally, the decreasing costs of solar and wind technologies further enhance the attractiveness of NZEBs in SSA (IRENA, 2021).

Although NZEBs are considered a potential solution for SSA, the application has been relatively insignificant. Several barriers hinder their implementation, such as the high initial costs of RES, the lack of access to finance, inadequate energy infrastructure, and weak policy frameworks (Obasanjo, 2018). Moreover, many studies in the region focus primarily on the techno-economic feasibility of NZEBs, while overlooking the integration of environmental sustainability aspects such as land use and the reduction of carbon emissions and deforestation aspects (Wang et al., 2019; Wei & Skye, 2021). Several research efforts have investigated the application of RES in building energy systems, with some studies addressing the optimization of HRES. For instance, (Mahamat et al., 2024; Medjo Nouadje et al., 2024) optimization methods such as genetic algorithm to carry out the optimal design of energy systems developed for a building. However, these studies generally focus on technical and economic outcomes without including environmental effects such as avoided deforestation and land use change, which are particularly important in SSA. In addition, although optimization methods like MOGA have been previously used in different domains, they are not extensively used for the SSA based optimization of NZEBs.

One of the most common gaps in the literature is that existing optimization models for NZEBs do not consider both technical and environmental goals together. This involves estimating land use requirements for NZEBs, environmental impacts of upwards deployment of RES and ramifications of avoided deforestation that are highly relevant in the context of SSA's rapidly expanding populations and increasing demands on land. Additionally, there is little empirical evidence about the incorporation of NZEBs to grid systems in SSA, namely energy resilience and reducing TET to the grid. The majority of available studies on NZEBs in SSA have interpreted the term as a purely technical or economic one without paying due attention to environmental dimensions, such as land use, deforestation or emission reduction. Moreover, the potential of NZEBs has been increasingly acknowledged in SSA, but only a few studies can be found to deal with region-specific case studies that reflect on local challenges and opportunities for implementation of these technologies. Finally, there is not enough emphasis on the integration of NZEBs with available grid infrastructure, which should be done especially to strengthen energy resilience and decrease their reliance from the grid with TET optimization.

The objective of this work is to design and optimize a HRES incorporating solar PV, WT, BSS and HSS based on MOGA to solve various optimization objectives (cost, energy reliability and environmental sustainability). The study evaluates the techno-economic and environmental performance of the system including reductions in CO_2 emissions, land use and avoided deforestation. It also compares two optimization methods: minimizing ACS and LPSP respectively TET for the purpose of enhancing energy autonomy and grid stability.

The novelty of this study lies in presenting a multi-objective optimization model for NZEBs in SSA that considers both technical and environmental aspects. The study presents a specific example from Kenya, which provides a model for the adoption of NZEBs in other SSA countries. It demonstrates the environmental benefits of NZEBs in terms of avoided deforestation, land requirement and provides steps that local policymakers can take to spur adoption of NZEBs, such as energy efficient building codes, financial incentives, and grid modernization strategies.

3. Materials and method

3.1. Proposed NZEBs system modeling

The case study presented in this research focuses on the Chiromo campus of the UoN, located at the geographic coordinates (1°16'26.1"S 36°48'19.0"E), with a 300 KW peak power demand, to fulfill this load demand, we proposed a grid-connected PV and wind as RES generation with battery and hydrogen as backups storage options to minimize energy purchasing from the grid. The proposed NZEBs block diagram is shown in Figure 1. In addition to the hourly load demand, we used the hourly meteorological data (irradiation, temperature and wind speed) for a year of the studied area and the techno-economic parameters of the main components from the literature (Table 1) during the modeling of the proposed NZEBs (Mahamat et al., 2024; Medjo Nouadje et al., 2024; Tiam Kapen et al., 2022).

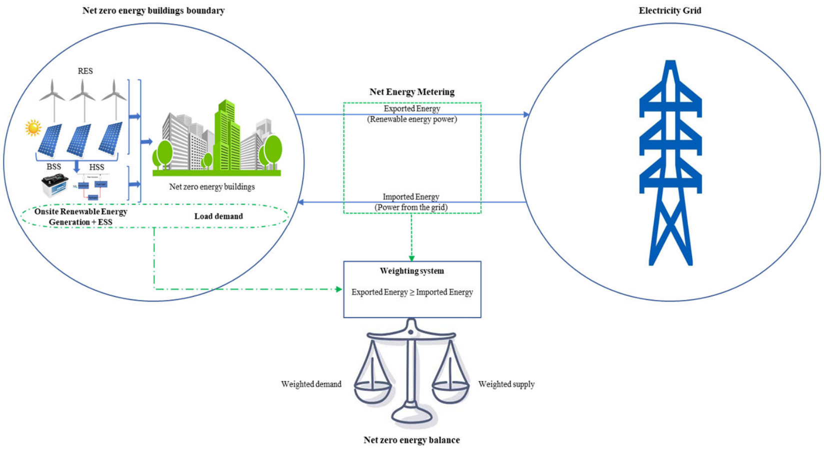


Figure 1: Proposed NZEBs block diagram.

Table 1: Techno-economic parameters utilized in NZEBs optimization processes.

Components	Capital cost	Operation & Maintenance cost	Replacement cost	Lifespan
PV	724 $/KW	20$/year	724 $/KW	20 years
Wind turbine	690.41 $/KW	60$/year	690.41 $/KW	20 years
Battery	203 $/kWh	10$/year	203 $/kWh	10 years
Electrolyzer	1850 $ / kW	30 $ / year	1573 $ / kW	5 years
Fuel cell	370 $ / kW	0	370 $ / kW	5 years
Hydrogen tank	734 $ / Kg	0	734 $ / Kg	20 years
Inverter	184 $ / kW	0	184 $ / kW	10 years
Inflation rate	10%	-	-	-
Project	-	-	-	20 ears

3.2. Mathematical modeling of the proposed NZEBs

In this section, the mathematical modeling of the main component of the proposed systems is presented.

3.2.1. Solar PV modeling

Equation (1) gives the outpower of the PV generator (Naderipour et al., 2021):

$$P_{PV}(t) = P_{r,PV} \times \left(\frac{S_{ir}}{S_{ref}}\right) \times EF_{MPPT} \quad \text{(eq. 1)}$$

Here $P_{r,PV}$, S_{ir}, $S_{ref,}$ EF_{MPPT}: The PV-rated power, solar irradiation, reference solar irradiation, and PV maximum point tracking efficiency are represented, respectively.

3.2.2. Wind turbine modeling

Equation (2) determines the generated outpower of the wind turbine (Niveditha & Rajan Singaravel, 2022):

$$P_{WT}(t) = \begin{cases} 0 & \text{if } V_{ci} > V(t) > V_{co} \\ P_r \dfrac{V(t)^3}{(V_r^3 - V_{ci}^3)} - P_r \dfrac{V_{ci}^3}{(V_r^3 - V_{ci}^3)} & \text{if } V_{ci} < V(t) < V_r \\ P_r & \text{if } V_r < V(t) < V_{co} \end{cases} \quad \text{(eq. 2)}$$

Where Pr, Vr, Vci, Vco, and V are, respectively, the rated power, the rated speed, the cut-in speed, the cut-out speed, and the wind speed.

3.2.3. Inverter modeling

The power of the inverter can be computed using equation (3) (Mahamat et al., 2024):

$$P_{inv}(t) = \frac{P_{load}(t)}{\eta_{inv}} \quad \text{(eq. 3)}$$

Here $P_{load}(t)$ signifies the hourly load requirement while η_{inv} refers to the efficiency of the inverter. inverter size is calculated based on equation (4) (Mahamat et al., 2024):

$$P_{inv,rated} = \frac{P_{L,peak}}{\eta_{inv}} \quad \text{(eq. 4)}$$

Where $P_{inv,rated}$ represents the power rating of the inverter while $P_{L,peak}$ is the peak load.

3.2.4. Battery storage system (BSS) modeling

BSS systems are rechargeable batteries created to store power generated by solar panels and wind turbines ($P_T(t) = P_{PV}(t) + P_{WT}(t)$), Which is then supplied to NZEBs (Ma & Yuan, 2023).
The surplus energy generated by solar and wind first charges the battery as per equation (5) (Wankouo Ngouleu et al., 2023) :

$$BSS(t) = BSS(t-1)(1-\sigma) + (P_T(t) - P_{inv}(t))\eta_{BSS_C} \quad \text{(eq. 5)}$$

When the load demand exceeds the available power from the PV and wind, BSS discharges energy to meet the load demand equation (6) (Mahamat et al., 2024; Wankouo Ngouleu et al., 2023) :

$$BSS(t) = BSS(t-1)(1-\sigma) - (P_{inv}(t) - P_T(t))\eta_{BSS_D} \quad \text{(eq. 6)}$$

Here σ, η_{BSS_C}, η_{BSS_D} are the self-discharge, the charging, and the discharging efficiency of the battery, respectively.

3.2.5. Hydrogen storage system (HSS) modeling

Any excess generated electricity from PV and wind sources in the proposed NZEB system is used to charge the battery when it exceeds the load demand. Alternatively, any surplus power is used to produce hydrogen for storage in the hydrogen storage tank (HT) (Mahamat et al., 2024). The amount of hydrogen intended for storage in HT is represented by equation (7) (Acakpovi et al., 2020; Wankouo Ngouleu et al., 2023) :

$$E_{Tank}(t) = E_{Tank}(t-1) + (P_T(t) - P_{inv}(t)) \times \eta_{Ez} \times \Delta t \quad \text{(eq. 7)}$$

In cases where the total power generated by solar panels (PV) and wind turbines is not enough to fulfill the required energy demand, stored hydrogen is then used from before to supplement the power deficiency through a fuel cell (FC). Hence, the quantity of hydrogen in the hydrogen tanks at time 't' can be represented by equation (8) (Wankouo Ngouleu et al., 2023):

$$E_{Tank}(t) = E_{Tank}(t-1) - (P_{inv}(t) - P_T(t)) \times \frac{\Delta t}{\eta_{FC} \times \eta_{str}} \quad \text{(eq. 8)}$$

Here η_{str}, η_{Ez}, η_{FC}, $E_{Tank}(t)$, and $E_{Tank}(t-1)$, are respectively the HT, the electrolyzer, the and FC efficiencies, the stored hydrogen amounts in kWh in HT at times t and t-1.

3.2.6. Grid interaction modeling

When the proposed NZEBs system fails to meet the total load requirements i.e., $P_{PV}(t) + P_{WT}(t) + P_{BSS}(t) + P_{HSS}(t) < P_{load}(t)$ the grid will provide the extra power required. In this instance, the grid serves as a form of backup. The expression of grid-imported power is depicted by equation (9) (Mahamat et al., 2024):

$$P_{Grid_{Imported}}(t) = P_{load}(t) - \sum_{t=1}^{8760} (P_{PV}(t), P_{WT}(t), P_{BES}(t), P_{FC}(t)) \quad \text{(eq. 9)}$$

Similarly, if $P_{PV}(t) + P_{WT}(t) + P_{BSS}(t) + P_{HSS}(t) > P_{load}(t)$, the extra power will be sent to the grid. Modeling the power exported to the grid is represented by the following equation, noted as equation (10) (Mahamat et al., 2024) :

$$P_{Grid_{exported}}(t) = \sum_{t=1}^{8760} \left(P_{PV}(t), P_{WT}(t), P_{BES}(t), P_{FC}(t)\right) - P_{load}(t) \quad \text{(eq. 10)}$$

The NZEBs balance concept, shown in Figure 1, can be mathematically explained by either the equation for imported and exported energy balance (equation (11)) or the equation for load and RES generation balance (equation (12)) (Deng et al., 2014). Ensuring a proper equilibrium between energy usage and production is generally seen as a crucial necessity in the planning stage of NZEBs. The balance of export and import energies, on the other hand, is crucial to assess the match between load and RES generation, as well as the interaction between the NZEBs and the grid (Lu et al., 2019).

$$\text{Net Energy} = |\text{Exported Energy}| - |\text{Imported Energy}| \geq 0 \quad \text{(eq. 11)}$$

i.e. $\sum_{t=1}^{8760}\left(\text{Exported}_{\text{Energy}}(t) \times \text{Weight}(t)\right) - \sum_{t=1}^{8760}\left(\text{Imported}_{\text{Energy}}(t) \times \text{Weight}(t)\right) \geq 0$

$$\text{Net Energy} = |\text{Onsite Generation}| - |\text{Load demand}| \geq 0 \quad \text{(eq. 12)}$$

i.e. $\sum_{t=1}^{8760}(\text{Onsite Generation}(t) \times \text{Weight}(t)) - \sum_{t=1}^{8760}(\text{Load demand}(t) \times \text{Weight}(t)) \geq 0$

In this study to enhance the NZEBs reliability with the grid interaction, we considered three (3) criteria: the $P_{Grid_{Imported}}(t)$ (equation (9)), the $P_{Grid_{exported}}(t)$ (equation (10)), and the TET associated with the grid and the NZEBs (equation (13)) (Huang et al., 2018; Niveditha & Rajan Singaravel, 2022; Sartori et al., 2012; S. Zhang et al., 2016).

$$TET(t) = P_{Grid_{exported}}(t) + P_{Grid_{Imported}}(t) \quad \text{(eq. 13)}$$

3.2.7. Annualized cost of system (ACS) analysis

The ACS includes the CRF (Capital Recovery Factor) as part of its computation. The CRF can be used to calculate the current value of this, adding accuracy to financial calculations. The calculation uses equation (14) for the analysis (Mahamat et al., 2024) :

$$CRF = \frac{i_r \cdot (1 + i_r)^N}{(1 + i_r)^N - 1} \quad \text{(eq. 14)}$$

This study considers a 10% interest rate (i_r) and the system's lifespan is represented by N.

The equations (15) - (21) provides the ACS for the various components (Mahamat et al., 2024):

$$PV_{cost} = N_{PV} \cdot [(C_{PV} \cdot CRF) + PV_{OM}] \quad \text{(eq. 15)}$$

$$WT_{cost} = N_{WT} \cdot [(C_{WT} \cdot CRF) + WT_{OM}] \quad \text{(eq. 16)}$$

$$Inv_{cost} = Inv_{size} \cdot [(C_{Inv} \cdot CRF) + Inv_{OM}] \quad \text{(eq. 17)}$$

$$\mathrm{Bat_{cost}} = \mathrm{N_{Bat}} \cdot [(\mathrm{C_{Bat}} + \mathrm{Replacement_{cost}}) \cdot \mathrm{CRF} + \mathrm{Bat_{OM}}] \quad \text{(eq. 18)}$$

$$\mathrm{FC_{cost}} = \mathrm{N_{FC}} \cdot [(\mathrm{C_{FC}} + \mathrm{Replacement_{cost}}) \cdot \mathrm{CRF} + \mathrm{FC_{OM}}] \quad \text{(eq. 19)}$$

$$\mathrm{EZ_{cost}} = \mathrm{N_{EZ}} \cdot [(\mathrm{C_{EZ}} + \mathrm{Replacement_{cost}}) \cdot \mathrm{CRF} + \mathrm{EZ_{OM}}] \quad \text{(eq. 20)}$$

$$\mathrm{HT_{cost}} = \mathrm{N_{HT}} \cdot [(\mathrm{C_{HT}} \cdot \mathrm{CRF}) + \mathrm{HT_{OM}}] \quad \text{(eq. 21)}$$

Where $\mathrm{C_{PV}}, \mathrm{C_{WT}}, \mathrm{C_{Inv}}, \mathrm{C_{Bat}}, \mathrm{C_{FC}}, \mathrm{C_{EZ}}$, and $\mathrm{C_{HT}}$ are the capital cost of PV modules, wind turbines, inverter, battery, FC, electrolyzer, and HT respectively. $\mathrm{N_{PV}}, \mathrm{N_{WT}}, \mathrm{N_{Bat}}, \mathrm{N_{FC}}$, and $\mathrm{N_{HT}}$ are the number of PV panels, wind turbine, battery, fuel cell, and hydrogen tank respectively. $\mathrm{Inv_{size}}$ represents the power rating of the inverter. And $\mathrm{PV_{OM}}, \mathrm{WT_{OM}}, \mathrm{Inv_{OM}}, \mathrm{Bat_{OM}}, \mathrm{FC_{OM}}, \mathrm{EZ_{OM}}$, and $\mathrm{HT_{OM}}$ are the operations and maintenance cost of the PV modules, wind turbine, battery, FC, electrolyzer and HT respectively.

The ACS is obtained from equation (22):

$$\mathrm{ACS} = \mathrm{PV_{cost}} + \mathrm{WT_{cost}} + \mathrm{Inv_{cost}} + \mathrm{Bat_{cost}} + \mathrm{FC_{cost}} + \mathrm{EZ_{cost}} + \mathrm{HT_{cost}} + \mathrm{NCG} \quad \text{(eq. 22)}$$

3.3. Criteria for evaluating proposed NZEBs performance

3.3.1. Loss of Power Supply Probability (LPSP)

The LPSP is a standard utilized to assess the dependability of NZEBs and can be applied to gauge the financial and environmental advantages of RES, ESS, and grid trade (Mahamat et al., 2024). The LPSP determines when power from RES falls short of fulfilling the load requirement with desired reliability (Xu et al., 2021; Yang et al., 2022; W. Zhang et al., 2019) according to equation (23):

$$LPSP = \frac{\sum_{t=1}^{8760} P_{deficit}(t) \cdot \Delta t}{\sum_{t=1}^{8760} P_{load}(t) \cdot \Delta t}, \Delta t = 1\ hour \quad \text{(eq. 23)}$$

3.3.2. Levelized Cost of Energy (LCOE)

The LCOE ($/kWh) is the total ACS divided by the total supplied energy over the year, equation (24) (Li et al., 2024; Shahverdian et al., 2023; Vakili et al., 2022):

$$\mathrm{LCOE} = \frac{\mathrm{Total_{ancost}}}{\sum_{t=1}^{8760}(\mathrm{P_{load}}(t) + \mathrm{P_{Grid_{exported}}}(t))dt} \quad \text{(eq. 24)}$$

3.3.3. Payback period (PBP)

The energy PBP is one of the criteria used to determine the energy benefits of NZEBs in in comparison to traditional options (Armendariz-Lopez et al., 2018). It is determined as per equation (25) (Al-Ghussain et al., 2024):

$$\mathrm{PBP} = \frac{\text{Initial investment}}{\text{Total revenue generated through electricity}} \quad \text{(eq. 25)}$$

3.3.4. Avoided carbon dioxide (ACO_2)

The annual avoided CO_2 of the NZEBS (in Kg) is evaluated using equation (26) (Mahamat et al., 2024). This indicates the volume of CO_2 emissions that are avoided from being released into the atmosphere through the use of RES instead of fossil fuel (Alshammari & Asumadu, 2020).

$$\mathrm{Avoided_{CO_2}} = (\mathrm{SO_X} + \mathrm{NO_X} + \mathrm{CO_2}) \cdot (0.001) \cdot \left(\sum_{t=1}^{8760} \mathrm{P_{load}}(t)dt - \sum_{t=1}^{8760} \mathrm{P_{Grid_{Sup}}}(t)\,dt\right) \quad \text{(eq. 26)}$$

The emission factors for carbon dioxide, nitrogen oxides, and sulfur oxides are CO_2=690 gCO_2/ kWh, NOX=0.22 gNOx/ kWh, and SOx=0.5 gSOx/ kWh,respectively (Ackermann et al., 2001; Mahamat et al., 2024; Peng et al., 2013), and 0.001 is the conversion factor from grams to kilograms.

3.3.5. Avoided deforestation

To estimate the avoided deforestation in this study we converted the amount of avoided CO_2 from RES into equivalent number of trees and then estimated the equivalent area covered by these trees. According to (US Environmental Protection Agency, 2023) a typical tree can absorb about 21.77 kg of CO_2 per year. The equivalent number of trees can be calculated by using the equation (27):

$$\text{Number of trees} = \frac{\text{Avoided}_{CO_2}(\text{kg})}{21.77} \quad \text{(eq. 27)}$$

This is a simplified calculation, and actual results may differ due to various factors, such as the species and age of the trees, local climate conditions, and others (US Environmental Protection Agency, 2023).

Knowing the number of trees can help to find the estimative equivalent area covered by a planted tree. According to (Ritchie & Roser, 2021) the planet earth has around 3.04 trillion trees. The overall forest area comprises approximately 26% of the total land area. If we estimate that the overall land area of the Earth is around 149 million square kilometers, then the total forest area would be approximately 38.74 million square kilometers. The estimative area covered by a single tree is shown in equation (28):

$$\frac{38.74 \text{ nillion square kilometers}}{3.04 \text{ trillion trees}} \approx 0.0000127 \text{ square kilometers/tree} \quad \text{(eq. 28)}$$

Therefore, the total estimative equivalent area covered by the trees in this study is calculated by using the equation (29):

$$\text{Estimative equivalent area} = \text{Number of trees} \times 0.0000127 \text{ square kilometers/tree} \quad \text{(eq. 29)}$$

3.3.6. Fraction of Renewable Energy (REF)

REF quantifies the proportion of RES in the overall power supply of the NZEBs as shown in equation (30). A greater REF indicates a greater proportion of RES and reduced reliance on fossil fuels. Therefore, a REF value approaching 100% is more favorable (Khan et al., 2021; Mahamat et al., 2024).

$$\text{REF} = 100 \cdot \left[1 - \left(\frac{\sum_{t=1}^{8760} P_{\text{Grid}_{\text{Imported}}}(t)}{\sum_{t=1}^{8760} P_{\text{load}}(t)}\right)\right] \quad \text{(eq. 30)}$$

3.3.7. Land requirement (LR)

The availability of land is finite, and any economic activity requires people's consent. It is one of the crucial criteria that is frequently neglected during the optimization of the NZEBs, yet it profoundly impacts the livelihoods of farmers who depend on agriculture for a living. The LR is calculated using equation (31) (Kushwaha et al., 2023):

$$\text{LR} = N_{\text{PV}} \times PV_{area} + N_{\text{W}} \times WT_{area} + N_{\text{bat}} \times BSS_{area} + N_{\text{Inv}} \times Inv_{area} + N_{\text{HSS}} \times HSS_{area} \quad \text{(eq. 31)}$$

Where PVarea (LR= 5.93 m2/kW), WTarea (LR= 110 m2/kW), BSSarea (LR= 0.10 m2/kW), Invarea (LR= 0.15 m2/kW), HSSarea (LR= 0.17 m2/kW) are respectively PV, wind turbine, battery, inverter, and hydrogen storage system total areas (IRENA, 2020; Kushwaha et al., 2023), and NPV, Nw, Nbat, Ninv, NHSS=$N_{HT} + N_{EZ} + N_{FC}$ are respectively PV, Wind turbine, BSS and HSS numbers.

3.4. NZEBs optimization approach

Based on the data and criteria outlined in Sections 3.1, 3.2, and 3.3, this study intends to find the most efficient sizing for the grid-connected PV, Wind, BSS, and HSS to fulfill the required load demand of the analyzed NZEBs. Figure 2 illustrates the optimization process utilized in this study for modeling the proposed system. The modeling was conducted using the MATLAB R2024a environment, which implemented a MOGA for the control dispatch. The proposed control dispatch aims to establish the most suitable size for every component (using equations (1) – (13)) and the best management of energy and power flow among the different elements of the proposed system (illustrated in Figure 3) to satisfy the NZEBs load demand with optimal reliability (minimum LPSP), lowest cost (minimum ACS (equation (22))), and minimum TET to the grid while acquiring the values of every criterion considered by this study using equations (23)– (31), which stand for the variables being considered in this feasibility analysis.

The ACS, LPSP, and TET were chosen as objective functions (OF) to examine the proposed system's higher reliability, financial feasibility, and the reduced reliance of NZEBs on the grid with minimal total energy transfer. Equations (32) – (33) express the OF and the variable constraints considered in this study (Mahamat et al., 2024):

$$OF = \begin{cases} Min(ASC) = f(PV, WT, BSS, HSS, Grid) \\ Min(LPSP) = f(PV, WT, BSS, HSS, Grid) \\ Min(TET) = f(PV, WT, BSS, HSS, Grid) \end{cases} \quad \text{(eq. 32)}$$

$$Subject\ to: \begin{cases} 20\% \le SOC_{Bat} \le 100\% \\ 5\% \le SOC_{HT} \le 100\% \\ N_x^{min} \le N_x \le N_x^{max} = \{PV, WT, BSS, HSS\} \end{cases} \quad \text{(eq. 33)}$$

Here SOC_{HT}, SOC_{Bat}, N_x^{min}, N_x, N_x^{max} are, respectively, the HSS and BSS's state of charge and N_x represents the number of components in the proposed system.

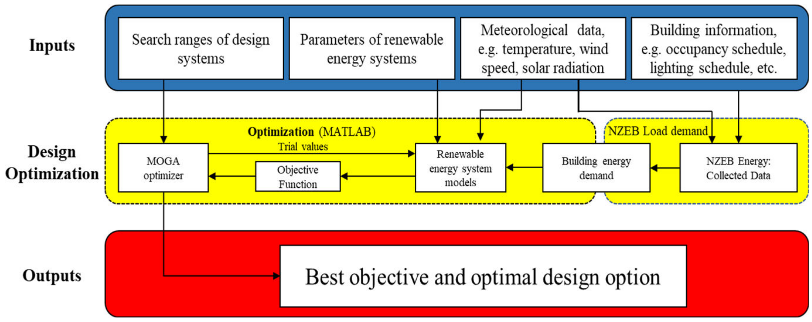


Figure 2: Optimization approach processes.

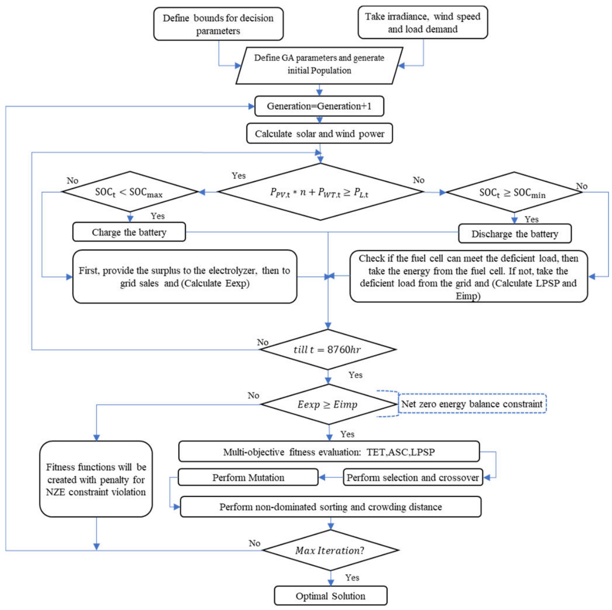


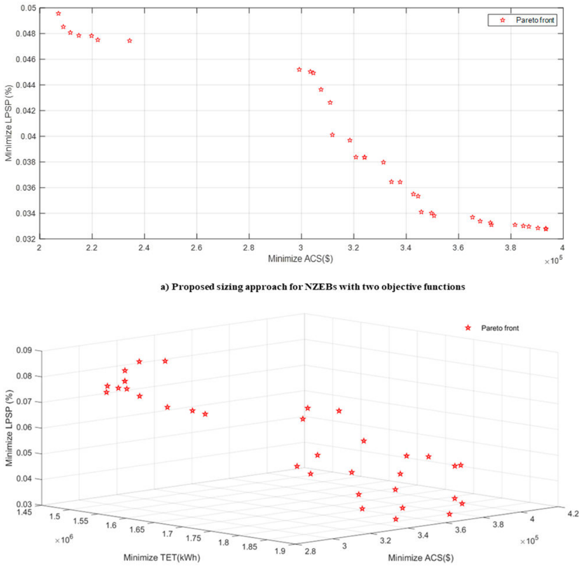
Figure 3: Control strategy flowchart of the proposed NZEBs system.

4. Results and Discussion

To meet the NZEB load demand and assess the system performance, two optimization models were developed for a grid-connected PV–Wind–BSS–HSS using MATLAB R2024a. The MOGA was implemented in two configurations:

1. Minimizing Annual Cost of the System (ACS) and Loss of Power Supply Probability (LPSP)
2. Minimizing ACS, LPSP, and Total Energy Transfer (TET)

Both models were tested under identical meteorological conditions with a fixed reliability level of LPSP = 0.0328, ensuring comparability of results. A population size of 100 and 50 generations were used to achieve Pareto-optimal front solutions. For both models, after 100 generations the MOGA algorithm converged to stable solutions. The primary objective was to obtain the best sizes of PV, WT, BSS and HSS that minimized the costs, ensured system reliability and decreased grid dependence. The pareto front solution set for both optimization methods is shown in Figure 4. It is clear from the analysis that ACS–LPSP–TET model yields a trade-off solution among multiple objectives; namely, minimizing ACS, LPSP and interaction with grid. For both sizing methods, the resultant solutions were technically equivalent and LPSP held at 0.0328%.

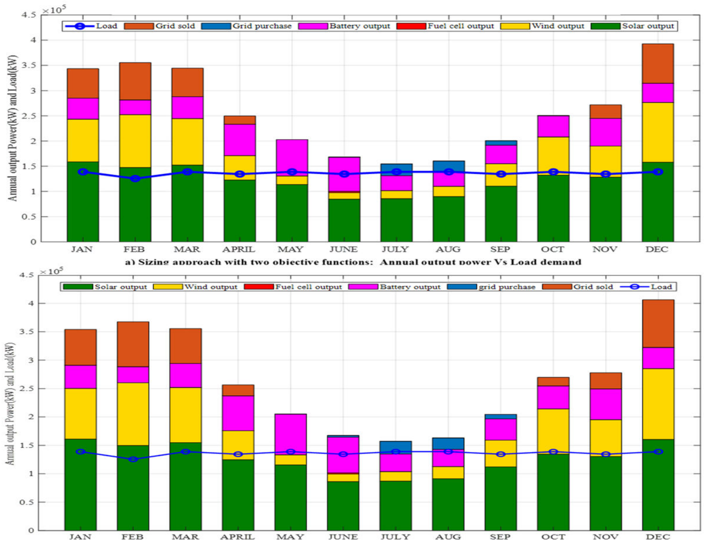


a) Proposed sizing approach for NZEBs with two objective functions

b) Proposed sizing approach for NZEBs with three objective functions

Figure 4: Pareto front solution set.

Solar generation continued to outperform power production driven by high annual irradiance, while wind output dropped from May through August caused by slow wind speeds. The BSS operated all the year round for peak shaving, but the HSS worked only when wind speed is low. Excess electricity was exported to the grid and deficits supplied from the grid, giving a balanced annual supply of power. Figure 5 reveals the annual power status of the designed NZEB under both sizing methods, while solar energy had been found as a major contributing component throughout the year (wind energy and BSS were only secondary contributors). The HSS was utilized predominantly during low wind generation periods.



a) Sizing approach with two objective functions: Annual output power Vs Load demand

b) Sizing approach with three objective functions: Annual output power Vs Load demand

Fig. 5: Proposed NZEBs yearly output power status for both sizing techniques.

Table 2 compares the performance of two NZEB sizing techniques across technical, economic, environmental, and grid interaction criteria to identify the most cost-effective and sustainable option. The optimal capacities for the PV–Wind–BSS–HSS system under the first approach (ACS, LPSP) are 976.6 kW for PV, 920 kW for the wind turbine, and 773.2 kW for the inverter. The system also includes 569,048.4 kWh / 546,618.5 kWh for battery charging/discharging, and 388.6 kW for the electrolyzer. The second approach (ACS, LPSP, and TET) shows slight increases in capacities: 987.14 kW for PV, 939.58 kW for wind, and 744.29 kW for the inverter, along with more favorable results in cost and payback period (PBP).

Both configurations demonstrated an identical REF of 96.72%, indicating that NZEBs are highly reliant on RES regardless of the optimization approach. However, the second approach, which incorporates TET, resulted in a slightly larger land requirement of 118,418 m², compared to 117,315 m² for the first method, which can be considered in areas with space constraints.

From a technical perspective, both approaches maintained a low LPSP of 0.0328%, demonstrating the reliability of the system in providing continuous power to meet the NZEB's energy demand. This is crucial for areas like the University of Nairobi, where energy reliability is paramount.

Economically, the second method (ACS, LPSP, and TET) showed significant improvements. The Levelized Cost of Energy (LCOE) decreased from \$0.24/kWh to \$0.21/kWh, and the PBP was reduced from 9.29 years to 8.03 years, showing improved financial performance. This makes the three-objective approach more appealing to investors and project managers, providing a competitive long-term cost.

Both methods were found to be environmentally equivalent. Each design saved around 1.09 million kg of CO_2 emissions per year, emphasizing the key role to be played by NZEBs in CO_2 mitigation. In addition, they both prevented deforestation in about 637,000 m², reinforcing the ecological benefit of NZEBs in preserving carbon sinks and protecting biodiversity.

The second method was further optimized for grid interaction: TET increased from 1,851,952 kWh to 1,874,484 kWh. This improvement reflects better energy management and stability by optimizing the interaction between the NZEBs and the central grid, especially during surplus energy production. The second approach, which requires slightly more land, delivers better economic, technical, and environmental performance, alongside improved grid interaction. This demonstrates its overall advantage for large-scale NZEB implementation in Sub-Saharan Africa.

Tab. 2: Proposed NZEBs performance evaluation criteria results

Résultats des critères d'évaluation des performances des NZEB proposés	Proposed two objectives function sizing technique (ACS &LPSP) results	Proposed two objectives function sizing technique (ACS, LPSP&TET) results
Total load demand (kWh)	163 5200	163 5200
PV capacity (kW)	976.6	987.14
Wind turbine capacity (kW)	920	939.58
Inverter capacity (kW)	773.2	744.29
BSS (charging / discharging) (kWh)	569048.4 / 546618.5	566759.39 / 544430.35
Electrolyzer size (kW)	388.6	379
Hydrogen energy (kWh)	4737.17	1066.56
Fuel cell output Energy (kWh)	2368.6	533.28
Levelized Cost of Energy (LCOE) (\$/kWh)	0.24	0.21
Payback period (PBP) (year)	9.29	8.03
Avoided carbon dioxide (ACO2) (Kg)	1092365.13	1092415.18
Avoided deforestation (m2)	637254.84	637284.01
Renewable Energy Fraction (REF) (%)	96.72	96.72
Land requirement (LR) (m2)	117315	118418
Total energy transfer (TET) (kWh)	1 851 952	1 874 484

5. Policy Implications and Recommendations

This study demonstrates the potential of by NZEBs to promote sustainable development, mitigate carbon emissions and improve energy security in the SSA. Policy makers can implement these lessons to accelerate the region’s transition toward a clean energy future:

- Support for NZEB Adoption: introduce policies for tax incentives and provide subsidies to overcome initial higher costs leading to the wider establishment of NZEB, along with up-to-date RES technologies.
- Policy: Integrate the environmental benefits from NZEBs, like lower CO_2 emissions and forest preservation, into national climate and conservation policies.
- Optimize Land Use: Utilize land requirements data to zone areas for RE infrastructure construction,

maintaining NZEBs integration without displacing essential agricultural or ecological domains.
- Foster Technological Innovation: Fund R&D of RE and advanced optimization techniques such as MOGA to enhance NZEB efficiency and performance.
- Enhance Energy Security: NZEBs should be embedded with national energy plans to diminish reliance on the grid and improve the energy resilience, reducing vulnerability to price variation of fossil fuels.
- Align with Global Climate Goals: NZEB implementation should receive priority as a strategic means for reaching carbon neutrality and the targets of the Paris Agreement.

6. Conclusion

This study confirms that NZEBs are both technically feasible and economically viable for Sub-Saharan Africa, with Kenya serving as a promising case. Through the application of a hybrid energy system on the University of Nairobi's Chiromo campus, integrating photovoltaic (PV), wind turbines (WT), battery storage (BSS), and hydrogen storage (HSS), the research demonstrates that NZEBs can effectively meet the region's growing energy demand. Using Multi-Objective Genetic Algorithms (MOGA), two optimization approaches were evaluated: one focusing on minimizing annual system costs (ACS) and unserved power loss (LPSP), and a second adding the objective of minimizing total energy transfer (TET).

The findings indicate that the three-objective model effectively diminishes dependence on grids, increases the energy efficiency and utilization ratio of renewable energy, achieves minimum carbon emissions and prevents deforestation. With some increase on land area requirements, this design guarantees much faster payback periods and better overall system performance. The NZEBs attain a superb 97% renewable fraction, contributing to environmental targets and climate change mitigation, saving more than one million kilograms of CO_2 per year.

The study offers strong evidence to afford policymakers the opportunity to hasten establishment of NZEBs within Sub Saharan Africa, thereby utilizing fiscal incentives, optimum land-use planning and clean energy policies. Incorporating NZEBs into their building stocks will help Kenya and other SSA nations strengthen energy security, stimulate economic development, and achieve international climate goals while preserving ecosystems. The results reveal that NZEBs constitutes a sustainable balance for energy, economic and environmental sustainability in the region.

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