Decarbonizing Power and Transport Sectors Through Renewable Integration: Battery, Hydrogen, and Power-To-Mobility Solutions

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Abstract

This study investigates the integration of electric vehicles (EVs) into the urban grid of Sub-Saharan Africa using an optimally sized hybrid renewable energy system combining solar PV, wind turbines, battery, and hydrogen storage. A Multi-Objective Dragonfly Algorithm (MODA) in MATLAB is used to minimize loss of power supply probability (LPSP), annualized system cost (ACS), and total energy transfer (TET). The system meets 96.3% of an annual EV load of 552,615 kWh with 272,001 kWh from solar and 315,239 kWh from wind. Grid interactions are limited, with 20,556 kWh imported and 36,006 kWh exported, while storage includes 224,995 kWh of battery discharge and 367.2 kWh of hydrogen. With a levelized cost (LCOE) of \$0.19/kWh, an 8.88-year payback period, and 367,503 kg of CO_2 emissions avoided, the system demonstrates a viable pathway for clean EV deployment in urban Sub-Saharan Africa.

Keywords: Grid integration of renewable power systems, electric vehicles, solar PV, wind power, battery storage, hydrogen storage, MODA, optimal sizing, Sub-Saharan Africa, urban electrification, techno-economic and environmental analysis

1. Introduction

Integrating electric vehicles (EVs) into the electric grid presents a significant challenge because of their high charging power demands (Chadha et al., 2022; Mahmud et al., 2023; Mojlish et al., 2025). Utilizing onsite renewable energy resources (RES) is a promising solution to address this challenge (Alhuyi Nazari et al. 2024). However, the challenge with using RES (solar and wind) is their intermittent nature, which leads to variable production over time, the seasons, and the weather (Hassan et al., 2023; Poddar et al., 2023; Wu & West, 2024; Ekoue et al., 2025). Energy storage systems (ESS) can majorly cover the time gap between energy production and consumption (De Carne et al. 2024; Dowling et al. 2020; Weitzel and Glock 2018). Hybridizing the RES and ESS could be an effective solution to EVs integration (Bocklisch 2015; Guven 2024; Ramesh and Balachander 2024). Oversizing or under sizing this complex hybrid system can lead to inefficiency and a less reliable system (Lian et al. 2019; Thirunavukkarasu, Sawle, and Lala 2023).

A Sub-Saharan African country with proven advancements towards renewable energy seems to be a fascinating experimental site for pathways on decarbonizing power and transportation. The paper presents a holistic methodology for techno-economic and environmental studies of the optimal sizing of grid-connected hybrid renewable energy system including solar photovoltaic (PV) and wind plants along with battery storage system (BSS), and hydrogen technology. The infrastructure for power-to-mobility can be supported with the efficient integration of electric vehicles (EV) and less dependence on fossil fuels. Optimization has been formulated to minimize three main objectives LPSP, ACS and TET. The procedure is developed in the MATLAB setting and based on a Multi-Objective Dragonfly Algorithm (MODA) that selects robust design alternatives for clean energy transformation and sustainable transportation in developing urban areas.

2. Materials and method

2.1. Study Area and Load Profile

The methodological framework and the main inputs data used in this work are depicted in Figure 1, where is shown the steps from (a) data gathering to (h) final assessment and optimization using Multi-Objective Dragonfly Algorithm (MODA). Figure 2. shows the hourly load demand for the chosen study area, which indicates a typical consumption characteristic as an example of daily profile. On the other hand, Figure 3 provides the annual profiles of solar

10.18086/swc.2025.06.11 Available at http://proceedings.ises.org

irradiance as well as ambient temperature and wind speed, respectively, which are crucial for estimating RE potential and system studies over time.

Figure 1: Modeling and Optimization Approach

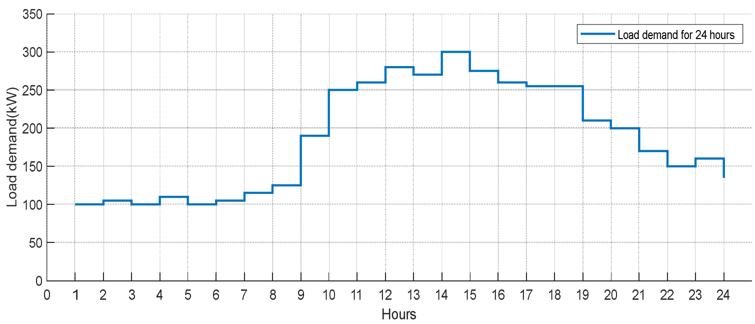

Figure 2: Study area's power demand for 24 hours

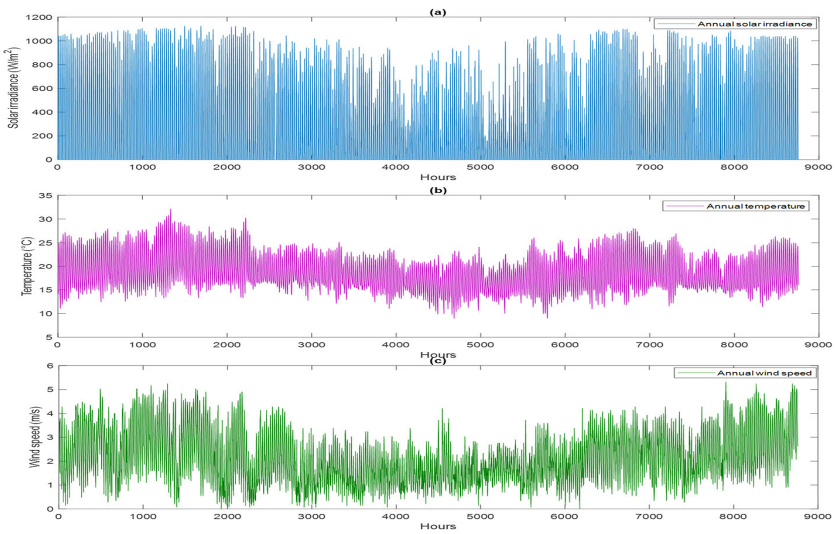

Figure 3: Annual meteorological data of the studied area

2.2. Operational and Energy Management Strategies (EMS) of the Proposed System

Figure 4 illustrates the configuration of the proposed hybrid energy system considered in this study, integrating multiple renewable and storage technologies to meet residential and electric vehicle energy demands

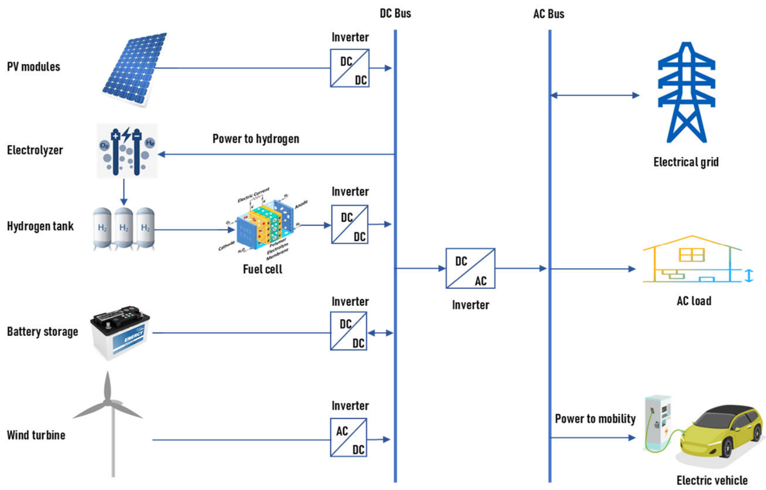

Figure 4: Proposed system: PV – Wind Turbine – Battery – Fuel cell – Grid – Electric vehicle

The EMS controller proposed in this study was designed using a rule-based algorithm implemented with if–else–then logic. The primary purpose of the EMS is to manage the flow of power between the different components of the system (Grid-Connected PV/WT/BSS/HSS for EV Charging). The controller is based on a cycle charging strategy and operates under the following modes:

Charging Mode:
Case 1: The energy produced by the PV and WT resources covers the energy load demand. The surplus energy will be utilized to charge the BSS ($E_{BSS}(t) < E_{BSS\_max}(t)$).
Case 2: The energy produced by the PV and WT resources surpasses the energy load demand and the BSS is fully charged ($E_{BSS}(t) = E_{BSS\_max}(t)$) then the excess energy will be used by the electrolyzer for H_2 production. In case the HT is also filled then the surplus energy will be used to charge EV (if it is available for charging) and remaining power will be sold to grid.

Discharging Mode.
Case 3: When the energy produced by the PV and WT resources is insufficient to meet the load demand ($E_{BSS}(t) > E_{BSS\_min}(t)$), the BSS discharges to cover the load demand.
Case 4: The energy produced by the PV and WT resources is not adequate to meet the load demand, and the BSS is depleted ($E_{BSS}(t) < E_{BSS\_min}(t)$). Then the FC together with the EV battery (if available) will supply the remaining demand.
Case 5: Incase the energy produced by the PV and WT resources cannot meet the load demand and both BSS and H_2 tank have been exhausted ($E_{BSS}(t) < E_{BSS\_min}(t)$). Then deficit energy is imported from grid to meet the load demand to ensure load reliability.

Figure 5 presents the flowchart for the EMS of the proposed grid-connected system, which integrates PV, WT, BSS, and HSS for EV charging.

2.3. Mathematical Modeling of System Components

This section describes the mathematical models for each of the important elements of system configuration, which provides a general structure to understand its behavioral nature.

2.3.1. Photovoltaic (PV) Model

Equation (1) gives the outpower of the PV generator (Das et al. 2017; Naderipour et al. 2021):

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

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.

2.3.2. Wind Turbine (WT) Model

Equation (2) determines the generated outpower of the WT (Niveditha and Rajan Singaravel 2022):

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

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.

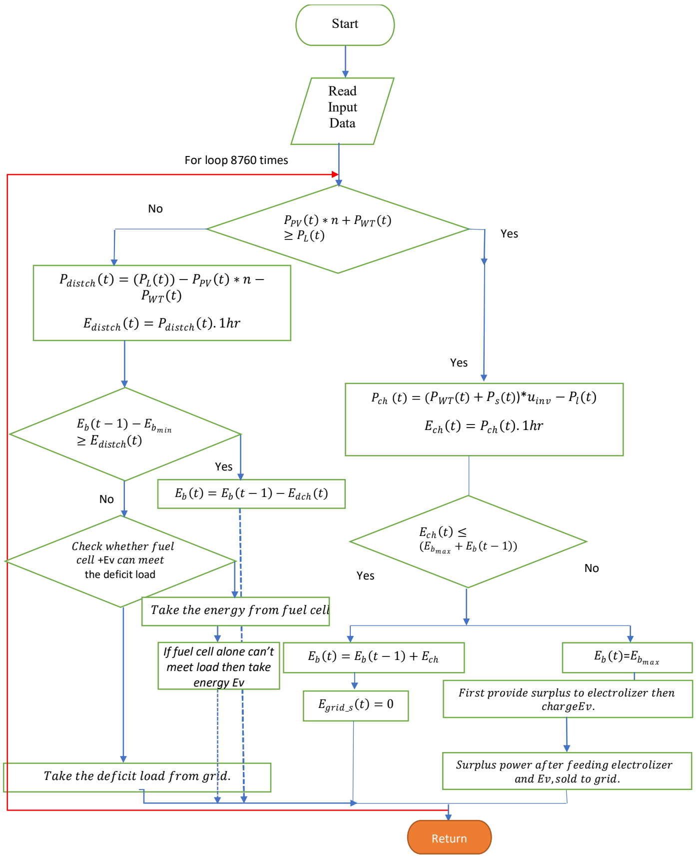

Figure 5: EMS Flowchart for Grid-Connected PV/WT/BSS/HSS-Based EV Charging

2.3.3. Battery Storage System (BSS) Modeling

The total hourly power output from the RES is given by Equation (3) (Mahamat et al., 2024):

$$P_T(t) = P_{PV}(t) + P_{WT}(t) \qquad \text{(eq. 3)}$$

Where $P_{PV}(t)$ and $P_{WT}(t)$ represent the hourly outputs power of the PV and WT, respectively.
The surplus energy generated by the solar and wind systems is first used to charge BSS, as described by equation (4) (Mahamat et al., 2024; Wankouo Ngouleu et al., 2023) :

$$BSS_{Charge}(t) = BSS(t-1)(1-\sigma) + (P_T(t) - P_{inv}(t))\eta_{BSS_C} \qquad \text{(eq. 4)}$$

When the load demand exceeds the available power from PV and WT, the BSS discharges energy to meet the load, as given by equation (5) (Mahamat et al., 2024; Wankouo Ngouleu et al., 2023) :

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

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

In these equations, the battery's state of charge (SOC) is updated based on its efficiency and the available surplus or deficit in power.

2.3.4. 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.

2.3.5. Inverter modeling

The power of the inverter can be computed using equation (9) (Mahamat et al., 2024):

$$P_{inv}(t) = \frac{P_{load}(t)}{\eta_{inv}} \quad \text{(eq. 9)}$$

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 (10) (Mahamat et al., 2024):

$$P_{inv,rated} = \frac{P_{L,peak}}{\eta_{inv}} \quad \text{(eq. 10)}$$

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

2.3.6. Electric Vehicle Charging Behavior Modeling

The integration of EVs within the power grid poses enormous opportunities and challenges. Mathematical modeling is required to maximize the charging process, control energy demand growth and efficiently use resources (del Giudice et al. 2023; İnci et al. 2024; Sultan et al. 2022).

- State of Charge (SOC) Update

The SOC of each EV battery is updated based on the charging power P_{charge} and the time spent charging Δt. The equation governing the SOC at each time step t is (equation (11)) (Alvarez Guerrero, Acker, and Castro 2022; Crozier, Morstyn, and McCulloch 2019):

$$SOC_i(t+1) = SOC_i(t) + \frac{\eta_{charge} \cdot P_{charge} \cdot \Delta t}{C_{EV}} \quad \text{(eq. 11)}$$

$SOC_i(t)$ is the SOC of the i-th EV at time t, η_{charge} is the charging efficiency, P_{charge} is the charging power (typically fixed), C_{EV} is the battery capacity of the EV (in kWh), and Δt is the time step (typically in hours).

This model assumes constant charging power and does not account for external constraints, leading to the possibility of energy consumption peaks that are uncoordinated with grid load, especially when many EVs are charging simultaneously.

- Energy Consumption

The total energy consumed by the EV over a period is (equation 12) (Alvarez Guerrero et al. 2022; Jaruwatanachai, Sukamongkol, and Samanchuen 2023; Powell et al. 2022):

$$E_{charge} = P_{charge}.\Delta t \quad \text{(eq. 12)}$$

2.4. Evaluation Criteria

2.4.1. Levelized Cost of Energy (LCOE)

LCOE (USD/kWh) is computed as the ratio of the TAC to the total electrical energy served over one year (Li et al. 2024; Shahverdian et al. 2023; Vakili, Schönborn, and Ölçer 2022) (equation 13) :

$$LCOE = \frac{ACS_{GC}}{\sum_{t=1}^{8760}(P_{load}(t) + P_{Grid_{exported}}(t))} \quad \text{(eq. 13)}$$

2.4.2. 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 14 (Al-Ghussain et al. 2024; Sohani, Rezapour, and Sayyaadi 2021):

$$\text{PBP} = \frac{\text{Initial investment}}{\text{Total revenue generated through electricity}} \quad \text{(eq. 14)}$$

2.4.3. Avoided Greenhouse Gas emissions (AGHG)

The annual avoided CO_2 of the proposed systems (in Kg) is evaluated using equation 15 (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 and Asumadu 2020).

$$\text{Avoided}_{\text{CO}_2} = (\text{SO}_\text{X} + \text{NO}_\text{X} + \text{CO}_2) \cdot (0.001) \cdot \left(\sum_{t=1}^{8760} \text{P}_\text{load}(t)dt - \sum_{t=1}^{8760} \text{P}_{\text{Grid}_\text{Sup}}(t)\,dt \right) \quad \text{(eq. 15)}$$

2.4.4. Renewable Energy Fraction (REF)

REF quantifies the proportion of RES in the overall power supply of the systems as shown in equation 16. 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).

$$\text{REF} = 100 \cdot \left[1 - \left(\frac{\sum_{t=1}^{8760} \text{P}_{\text{Grid}_\text{Imported}}(t)}{\sum_{t=1}^{8760} \text{P}_\text{load}(t)} \right) \right] \quad \text{(eq. 16)}$$

2.4.6. Grid interaction modeling

When the proposed NZEBs system fails to meet the total load requirements i.e., $\text{P}_\text{PV}(t) + \text{P}_\text{WT}(t) + \text{P}_\text{BSS}(t) + \text{P}_\text{HSS}(t) < \text{P}_\text{load}(t)$ 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 (17) (Mahamat et al., 2024):

$$\text{P}_{\text{Grid}_\text{Imported}}(t) = \text{P}_\text{load}(t) - \sum_{t=1}^{8760} (\text{P}_\text{PV}(t), \text{P}_\text{WT}(t), \text{P}_\text{BES}(t), \text{P}_\text{FC}(t)) \quad \text{(eq. 17)}$$

Similarly, if $\text{P}_\text{PV}(t) + \text{P}_\text{WT}(t) + \text{P}_\text{BSS}(t) + \text{P}_\text{HSS}(t) > \text{P}_\text{load}(t)$, 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 (18) (Mahamat et al., 2024) :

$$\text{P}_{\text{Grid}_\text{exported}}(t) = \sum_{t=1}^{8760} (\text{P}_\text{PV}(t), \text{P}_\text{WT}(t), \text{P}_\text{BES}(t), \text{P}_\text{FC}(t)) - \text{P}_\text{load}(t) \quad \text{(eq. 18)}$$

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 proposed system reliability with the grid interaction, we considered three (3) criteria: the $\text{P}_{\text{Grid}_\text{Imported}}(t)$ (equation (17)), the $\text{P}_{\text{Grid}_\text{exported}}(t)$ (equation (18)), and the TET associated with the grid and the proposed system (equation (19)) (Huang, Huang, and Sun 2018; Niveditha and Rajan Singaravel 2022; Sartori, Napolitano, and Voss 2012; Zhang, Huang, and Sun 2016).

$$\mathrm{TET(t)} = \mathrm{P}_{\mathrm{Grid}_{\mathrm{exported}}}(\mathrm{t}) + \mathrm{P}_{\mathrm{Grid}_{\mathrm{Imported}}}(\mathrm{t}) \quad \text{(eq. 19)}$$

2.5 Multi-Objective Dragonfly Algorithm (MODA)

2.5.1 Overview of the Optimization Framework

To determine the optimal sizing of the proposed grid-connected hybrid renewable energy system (HRES), a Multi-Objective Dragonfly Algorithm (MODA) was implemented in MATLAB. The optimization problem aims to simultaneously minimize three conflicting objective functions:

- Loss of Power Supply Probability (LPSP),
- Annualized System Cost (ACS),
- Total Energy Transfer (TET).

MODA is a swarm intelligence-based metaheuristic algorithm inspired by the static and dynamic swarming behaviors of dragonflies. The algorithm models five main interaction mechanisms: separation, alignment, cohesion, attraction toward food sources, and distraction from enemies. These behaviors enable a balanced trade-off between global exploration and local exploitation during the search process.

In this study, the decision variables include the sizing parameters of PV arrays, wind turbines, battery storage system (BSS), hydrogen storage system (HSS), and associated system components. The algorithm iteratively updates candidate solutions and constructs a Pareto front representing optimal trade-offs among LPSP, ACS, and TET.

2.5.2 Comparison with Previous MOPSO-Based Approach

In our previous study (Mahamat et al., 2024), a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm was applied for the optimal sizing of HRES under off-grid and simplified grid-connected configurations. While MOPSO demonstrated satisfactory performance in techno-economic evaluations, the system configuration considered in that work did not explicitly incorporate dynamic EV charging behavior, hydrogen storage integration, or grid-interactive energy exchange minimization.

The present study addresses a more complex and nonlinear optimization landscape due to:

- Integration of EV charging demand,
- Hydrogen production and storage management,
- Explicit modeling of grid-imported and grid-exported power,
- Inclusion of Total Energy Transfer (TET) as an additional objective.

Compared to MOPSO, MODA provides an improved exploration–exploitation balance through its dynamic swarming behavior. As reported by (Mirjalili, 2016), the dragonfly algorithm enhances global exploration via separation and alignment mechanisms while maintaining local exploitation through cohesion and attraction behaviors. This structure reduces the risk of premature convergence and improves Pareto front diversity in complex multi-objective optimization problems.

Accordingly, MODA was adopted in this study to enhance robustness, convergence stability, and solution diversity in the optimal sizing of the proposed grid-interactive renewable energy system. The principal methodological differences between MOPSO and MODA are summarized in Table 1 (Mirjalili, 2016; Kennedy & Eberhart, 1995).

Tab. 1: Comparison between MOPSO and MODA algorithms

Criterion	MOPSO	MODA
Inspiration mechanism	Particle velocity and position update	Static and dynamic dragonfly swarming behavior
Exploration capability	Moderate	High
Exploitation capability	Good	Enhanced adaptive local search
Risk of premature convergence	Medium	Reduced
Pareto front diversity	Limited in complex nonlinear systems	Improved diversity distribution
Suitability for grid-interactive multi-objective systems	Good	Very suitable
Handling of nonlinear constraints	Moderate	Improved robustness

3. Results and discussion

The main results obtained by the optimized system are presented in the subsequent sections, after a complete analysis of its energy performance and economic/environmental feasibility; further insights were provided to identify how the single levels contribute to overall efficiency and sustainability.

The optimal results of the proposed system are shown in Table 2, demonstrating that the proposed system can provide excellent energy performance capability as well as economic and environmental benefits. These findings evidence the capability of this system for successful renewable generation accommodation, secure energy supply for electric vehicles (EVs) and increasing affordability and environmental sustainability.

Tab. 2: Optimal results

Metric	Value	Implications
Total demand fulfillment (kWh)	552615	Sufficient capacity to meet EV and other loads
Payback period (PBP) (year)	8.88	Shows long-term economic feasibility
Avoided carbon dioxide (ACO_2) (Kg)	367503	Significant reduction in carbon footprint
Levelized Cost of Energy (LCOE) ($/kWh)	0.19	Cost-effective solution compared to grid power
Renewable Energy Fraction (REF) (%)	96.28	High self-sufficiency and renewable utilization
Total energy transfer (TET) (kWh)	566797.6	Efficient energy distribution across components

The entire 552,615 kWh energy needs of EV charging and facility loads are effectively satisfied by the system, with solar and wind energies accounting for the majority, to achieve sustainability and grid independence. The designed system is economically favorable to be paid back after 8.88 years suggesting that the initial investment is earned through savings in a long-run period. This further leads to avoiding 367,503 kg of CO_2 emissions and a very low carbon footprint in comparison with fossil-fuel-based systems which is crucial for climate change mitigation in rapidly growing urban areas, such as Sub-Saharan Africa. With the LCOE of $0.19/kWh, the system can serve as a reliable and cost-competitive substitution for grid power with economic rewards and environmental benefits. With a high REF of 96.28%, the system is relatively self-sufficient, reducing dependence on fossil fuels and making a significant contribution to goals for sustainable energy use. Using TET of 566,797.6 kWh, energy flow can be controlled on the system to utilise inverter power for increased renewable generation and manage storage efficiently for adequate supply balance.

- The Pareto front for the three-objective optimization is given in Figure 6 and shows that a penalty on TET helps reduce reliance on the grid, while promoting how local energy is used as it both reduces grid energy exchange and demands lower T_F, making this an attractive approach for areas with constraints or high import/export costs.

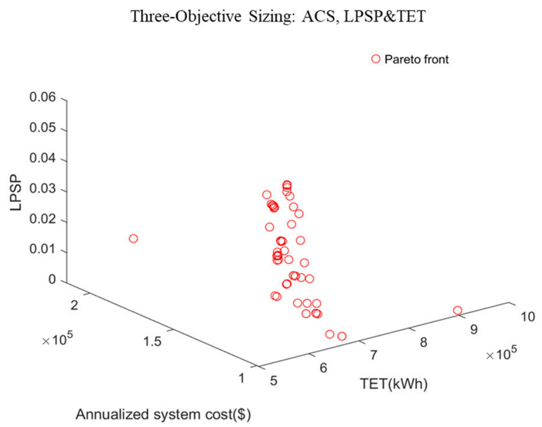

Figure 6: Pareto fronts for the two optimization strategies

As illustrated in Figure 7, the EV charging load is predominantly covered by renewable generation (solar PV and wind turbines), while the battery storage system (BSS) contributes to service reliability when renewable output fluctuates.

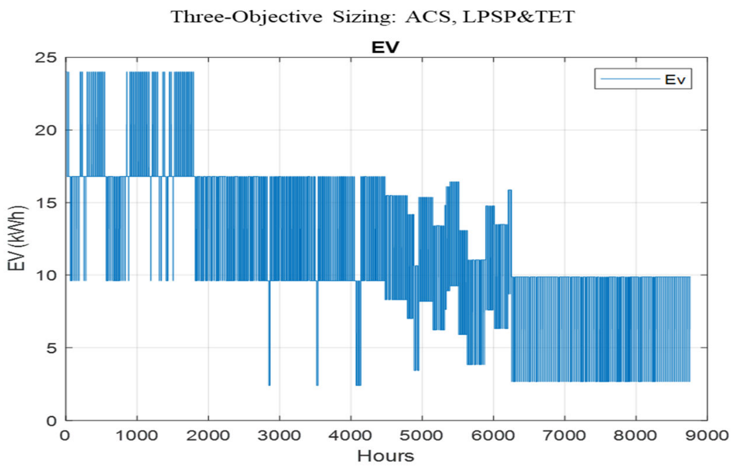

Figure 7: Annual energy delivered to the electric-vehicle charging load

The monthly energy exchanges are shown in Figure 8, where PV and WT cover most of the demand, while BSS faces short-term variations. Hydrogen storage system (HSS) as a backup, while available to compensate occasional lack of energy, here at least realize enhanced system resilience without overspending in hydrogen infrastructure.

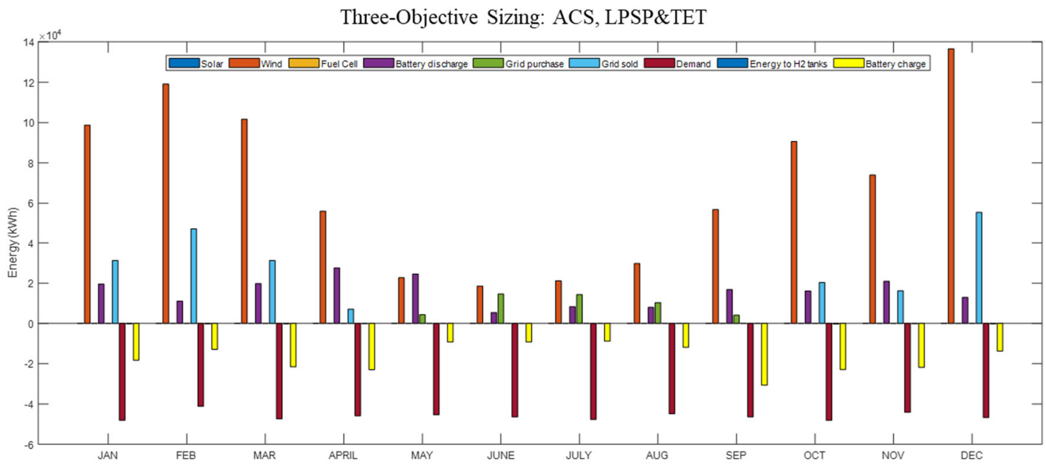

Figure 8: Monthly energy flows by component for the proposed systems

4. Conclusion

The findings of this work show that a grid-interactive solar PV and wind turbine, battery storage and hydrogen storage fed EV charging hub is an environmentally sustainable, economically viable and long-term solution to urban electrification especially in Sub-Saharan Africa. The system has a fulfilment rate of demand of 96.28% (552,615 kWh) by mainly renewable energy with minimum reliance on grid supply. With a cost of electricity (COE) at 0.19 USD/kWh, the payback period is only 8.88 years, which makes it an alternative to the grid power source with competitive price. Its also preventing 367,503 kg of CO_2 from being released into the atmosphere: more than holding its carbon footprint. A Total Energy Transfer (TET) of 566 797.6 kWh demonstrates high levels of effective energy usage across the distribution and storage management systems, to ensure that energy is consistently available in variable renewable generation conditions. The system's high Renewable Energy Fraction (REF) of 96.28% demonstrates its self-sufficiency and reduces dependence on fossil fuels. Such hybrid renewable energy system offers an economically viable and environmentally friendly approach for the grid integration of electric vehicles in urbanized areas with security of energy supply and clean sustainable mobility for developing countries.

Acknowledgments

This work is funded by the Regional Scholarship for Innovation Fund (RSIF), a flagship program of Partnership for Skills in Applied Sciences, Engineering and Technology (PASET) (No. B8501E21099).

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