Techno-Economic Analysis of a Hybrid Renewable Energy System in the Remote Areas in Kenya

Mulumba, Ngila Alphonce
九州大学大学院総合理工学府環境エネルギー工学専攻

出版情報：九州大学, 2022, 修士, 修士
バージョン：
権利関係：

TECHNO-ECONOMIC ANALYSIS OF A HYBRID RENEWABLE ENERGY SYSTEM IN THE REMOTE AREAS IN KENYA

Alphonce N. Mulumba, Hooman Farzaneh
Interdisciplinary Graduate School of Engineering Sciences, Kyushu University
6-1 Kasuga-koen, Kasuga-shi, Fukuoka 816-8580, Japan
E-mail: mulumba.alphonce.203@s.kyushu-u.ac.jp

ABSTRACT

Sub-Saharan Africa (SSA) has the lowest energy access rates globally. The need for transformative energy sources ranging from solar off-grid and mini-grid solutions to hybrid micro-grid power systems has rapidly grown in the quest to deliver clean energy admittance. This research proposes a hybrid photovoltaic-wind turbine power system coupled to a hybridized storage system composed of the lithium-ion battery and flywheel storage system. The system ensures reliability for off-grid electrification for rural and less accessible remote areas of Makueni County in Kenya.

Keywords: HRES, LCOE, EISR, Multi-objective optimization, Reliability, Pareto front, Epsilon(ε)-constraint technique, HESS, Flywheel.

INTRODUCTION

Off-grid microgrid hybrid renewable energy systems (HRES) combined with hybrid storage systems provide an accurate solution to power shortages in remote areas of the globe (Dehghani, Zhang, & Shafieezadeh, 2021). Renewable systems like photovoltaics, wind turbines, battery, and flywheel storage have significantly low maintenance costs, emissions, reliability, and flexibility (Fathima & Palanisamy, 2015). Numerous studies have applied several algorithms to achieve multi-objective optimization and formulation of HRES systems. Such methods include particle swarm optimization, goal programming, fuzzy logic approach, simulated annealing, and evolutionary genetic algorithms, among other multi-objective optimization techniques. Previous research has been done to explain the sizing of the HRES system as a fundamental approach to addressing renewable energy fluctuation issues occasioned by intermittency.

Contrary to the previous research works, this study establishes a convergence of optimum cost and energy reliability for the HRES system, providing an appropriate size for PV panels, wind turbines, and energy storage based on the multi-objective ε-constraint mathematical programming. Secondly, it demonstrates a dynamic power operation using Matlab/Simulink simulation for the optimal sizes achieved during optimization. The combination of solar and wind power generators to obtain the optimum power output of the system considering the cost of components, installation, operation-maintenance, and storage costs, while minimizing possible situations of power un-reliability is a unique part of research figured out in this study. Figure *1*Figure 1 represents the overall structure of the modeling framework developed.

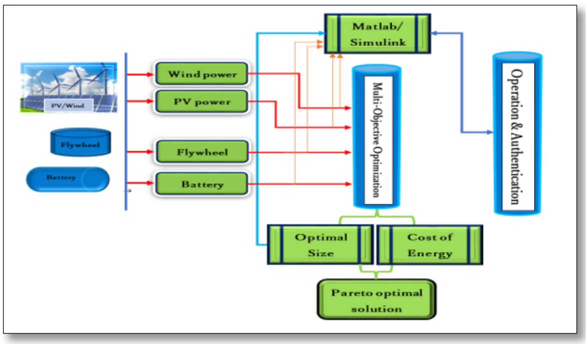

Figure 1: Modeling framework in this study

MULTI-OBJECTIVE OPTIMIZATION MODEL

This study develops a multi-objective optimization approach to determine the system's size, cost, and optimum reliability. The optimum solution enables desired decision in ensuring higher power reliability at affordable costs. The formulation of the multi-objective optimization algorithm is based on the cost of energy (COE) and the reliability index measured by the function of unmet energy (UME):

$$Min\ F(x) = \{f_{1(COE)}, f_{2(UME)}\}$$

Subject to:

$$\mathrm{P}_{\mathrm{PV(t)}} + \mathrm{P}_{\mathrm{WT(t)}} + P_{Bdch(t)} + P_{FWdch(t)} = \mathrm{P}_{\mathrm{L(t)}} + P_{Bch(t)} + P_{FWch(t)}$$

The total capital cost and annual operation and maintenance costs are summed, putting into consideration the Levelized Cost of Electricity generation (LCOE) from the proposed HRES as follows:

$$f_{1(COE)} = \left(\frac{IC_i + RC_i + OMC_i}{(1+r)^y}\right) / \left(\frac{P_{Gen}}{(1+r)^y}\right)$$

$$f_{2(UME)} = \sum_{t=1}^{T} \left\{\frac{\left(P_{Bdch(t)} + P_{FWdch(t)} + P_{L(t)} - P_{WT(t)} - P_{PV(t)} - P_{Bch(t)} - P_{FWch(t)}\right)}{P_{Gen(t)}}\right\}$$

Where:

$f_{1(COE)}$ and $f_{2(UME)}$ are the cost and reliability functions, IC_i, RC_i, OMC_i is the total annualized capital, replacement, operational and maintenance costs for the HRES components respectively, while r is discount rate and y component lifespan. $\mathrm{P}_{\mathrm{PV(t)}}$, $\mathrm{P}_{\mathrm{WT(t)}}$, $P_{Bch(t)}$, $P_{FWch(t)}$ represent solar, wind turbine, battery, and flywheel power at time t, so that $P_{Gen(t)}$ is total power generated at the same time.

SIMULATION MODEL

The Matlab/Simulink model shown in Figure 2 illustrates the dynamic modeling and simulation of the proposed HRES system. The system comprises 26 PV panels with a peak power output of 8.58kW, three wind turbines rated at 1kW, and hybrid storage made up of battery and flywheel storage systems.

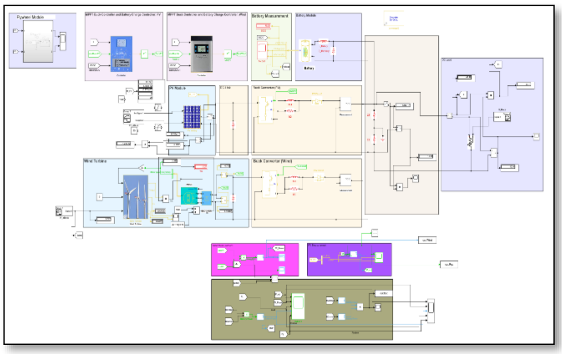

Figure 2: Dynamic modeling and simulation model

RESULTS AND DISCUSSION

In Figure 3, an illustration of the multi-objective optimization Pareto front for the NLP ε-constraint solution in GAMS is demonstrated. The values of COE and UME for the f_1 and f_2 objective functions are tabulated for each hour of the year (8760 hours), giving a suitable compromise solution. This is because a Pareto criterion exhibits a trading set-up in which neither side of the function merits without inversely affecting the other function. While the values of COE decrease, the values of EISR decrease, implying a reduced reliability state in the power supply if a lower cost of electricity is adopted.

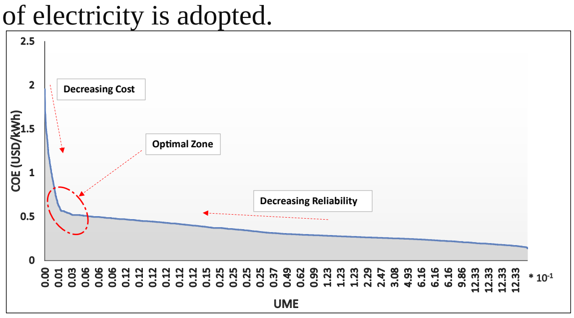

Figure 3: Pareto frontier GAMS Optimization

The optimal results for the HRES system multi-objective optimization using the epsilon (ε)-constraint technique are summarized in Table 1.

Table 1: Optimization results

Output Variable	Optimal Value
COE	0.519
UME	0.003
Number of PV modules (330Wp)	26
Wind Turbines (1kW Rating)	3
Battery Capacity (kWh)	22
Flywheel Capacity (kWh)	4.7

The simulation results in Figure 4 illustrate the operation output for the HRES system for an arbitrary 72-hour weather conditions scenario in Makueni during June 2021. The system results in visualization show an effective power balance and perfect complementation between the electrical load demand and power generation and between charging and discharging operations based on the given optimal size of the HRES. The hybrid storage system demonstrates high-frequency response and battery capacity gain of 858kWh/year.

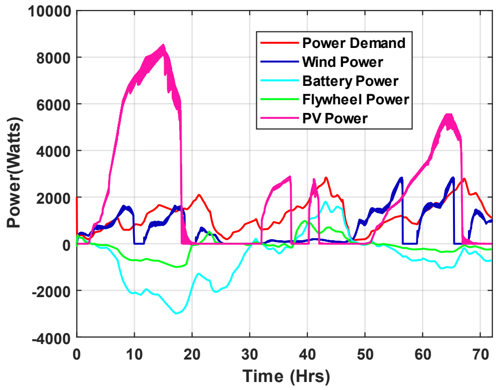

Figure 4: Overall system performance for 72 hours

CONCLUSION

The multi-objective optimization results for COE were realized at 0.519 USD/kWh depicting a suitable compromise for high-reliability levels and electricity affordability. The value of unmet energy, UME, was found at 0.00308, showing that HRES can supply electricity consistently. These results demonstrate the efficiency of the off-grid HRES system installed in a remote area with an annual electricity demand of 37.94MWh. The simulation results on Matlab/Simulink demonstrate the adequate performance of the proposed HRES. As demonstrated and discussed in this study, the flywheel storage system provides a fast dynamic response and high energy density necessary to avoid possible power outages. A comparison and analysis of battery storage capacity behavior both with and without hybrid storage in the HRES system shows a significant increment in capacity when the BESS-FESS storage system is assumed.

REFERENCES

Fathima, A. H., & Palanisamy, K. (2015). Optimization in microgrids with hybrid energy systems – A review. *Renewable and Sustainable Energy Reviews*, *45*, 431–446. https://doi.org/10.1016/J.RSER.2015.01.059

Amer, M., Namaane, A., & M'Sirdi, N. K. (2013). Optimization of hybrid renewable energy systems (HRES) using PSO for cost reduction. *Energy Procedia*, *42*, 318–327. https://doi.org/10.1016/J.EGYPRO.2013.11.03