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TECHNO-ECONOMIC FEASIBILITY AND OPTIMIZATION OF OFF-GRID HYBRID RENEWABLE ENERGY SYSTEMS FOR RURAL ELECTRIFICATION IN ETHIOPIA

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ABSTRACT

This study explores the techno-economic feasibility and optimal configuration of off-grid hybrid renewable energy systems (HRES) for rural electrification in Ethiopia. The proposed systems integrate solar photovoltaic (PV), wind turbines, and battery storage, with or without diesel backup, to ensure reliable and sustainable energy access in remote areas. Using HOMER Pro software, various system combinations were simulated based on local resource availability, load profiles, and economic parameters. The analysis reveals that optimized HRES configurations can significantly reduce the levelized cost of electricity (LCOE), greenhouse gas emissions, and reliance on fossil fuels. Solar-wind-battery systems, in particular, showed promising results in terms of cost-effectiveness and environmental sustainability. This work supports Ethiopia's energy access goals and provides a viable framework for clean energy implementation in underserved rural regions.

Keywords: Hybrid renewable energy system (HRES), rural electrification, techno-economic analysis, off-grid systems, solar PV, wind energy, battery storage, HOMER Pro, levelized cost of electricity (LCOE), Ethiopia.

INTRODUCTION

Global energy demand continues to rise, driven by population growth, industrialization, and technological advancements. However, a significant portion of the world's population, particularly in developing countries, still lacks access to reliable and affordable electricity. This energy poverty profoundly impacts socio-economic development, health, and education, hindering progress towards the United Nations Sustainable Development Goals (SDGs), especially SDG 7: "Ensure access to affordable, reliable, sustainable and modern energy for all" [8, 9]. The transition to sustainable energy systems, primarily relying on renewable and low-carbon sources, is paramount to address both energy access deficits and climate change concerns [2, 3, 7].

Sub-Saharan Africa faces a severe electrification challenge, with a substantial portion of its rural population remaining unelectrified. Ethiopia, despite its vast renewable energy potential, particularly in hydro, wind, and solar resources, struggles with a significant electricity access gap, especially in its rural areas [10, 31, 36, 37]. Extending the national grid to these remote and often sparsely populated regions is frequently economically unviable due to high infrastructure costs, challenging terrain, and low initial demand. This economic barrier makes conventional centralized grid expansion an impractical solution for achieving universal energy access in the short to medium term [11, 12, 14, 15, 17].

In this context, decentralized, off-grid energy solutions, such as standalone systems and mini-grids, offer a promising alternative for rural electrification [11, 12, 14, 15, 16, 17, 19]. Among these, hybrid renewable energy systems (HRES) are gaining increasing attention. HRES combine two or more renewable energy sources, often supplemented by energy storage systems (typically batteries) and sometimes conventional generators (like diesel generators), to provide a more reliable and consistent power supply than single-source systems [4, 5, 6, 20, 30]. The inherent intermittency of individual renewable sources like solar photovoltaic (PV) and wind power can be mitigated by combining them, leveraging their complementary generation profiles. For instance, wind resources may be strong when solar irradiance is low, and vice versa. The integration of energy storage further enhances reliability by buffering supply-demand fluctuations, storing excess energy during periods of high generation, and discharging during periods of high demand or low renewable output [4, 5].

Numerous studies have explored the feasibility of standalone and hybrid renewable energy systems in various regions, including different parts of Ethiopia [20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 33, 41, 43, 45, 46, 47]. These studies often highlight the technical viability of such systems, but a comprehensive techno-economic analysis, including optimization for specific Ethiopian rural contexts, is crucial for practical implementation. This article aims to perform a detailed techno-economic feasibility assessment and optimization of off-grid hybrid renewable energy systems tailored for rural electrification in Ethiopia. The study will evaluate different hybrid configurations, analyze their economic viability, reliability, and environmental impact, and identify the most optimal solutions to inform decision-making for sustainable rural energy development in the country.

METHODS

The methodology for this techno-economic feasibility and optimization study involved several key steps: site selection (representative rural characteristics), resource assessment, load profile estimation, system component modeling, hybrid system configuration, optimization using a specialized software tool, and detailed economic and technical analysis.

Study Area and Load Profile Estimation

Since the study aims to provide a generalized techno-economic analysis for rural Ethiopia, a specific village was not selected. Instead, representative characteristics of a typical remote Ethiopian rural community, lacking access to the national grid, were considered. This includes dispersed households, basic community facilities (e.g., school, health post, water pumping station), and a lack of existing electricity infrastructure.

The electrical load profile for a typical rural Ethiopian household and community facilities was estimated based on common electrical appliances used, their power ratings, and expected hours of operation. This included lighting (LED bulbs), televisions, mobile phone charging, small refrigeration units, and power for community services like water pumping and health clinics. A daily load profile with hourly variations was developed, accounting for peak demand periods (e.g., evenings for lighting, specific hours for water pumping) and off-peak periods. Seasonal variations in demand were also considered, reflecting changes in daylight hours and agricultural activities [10, 18, 32, 44, 48, 49, 50]. Total daily energy demand was aggregated to represent the community's needs.

Renewable Resource Assessment

Accurate assessment of available renewable energy resources is fundamental for the optimal design of hybrid systems.

1. Solar Irradiance Data: Hourly global horizontal irradiance (GHI) and clearness index data for a representative location in rural Ethiopia were acquired from reliable sources such as NASA's Surface Meteorology and Solar Energy database or local meteorological stations [21, 22, 26, 35, 45, 47, 50]. Long-term average daily and monthly values were used to capture seasonal variations.

2. Wind Speed Data: Hourly wind speed data at a standard hub height (e.g., 10 m or typical turbine hub height) for the same representative location were collected from similar databases or local measurements [21, 22, 23, 24, 35, 39, 45, 46, 47]. This data was analyzed to determine the wind speed distribution (e.g., Weibull parameters) and average wind power density.

System Components Modeling and Configuration

The hybrid energy system components were modeled based on their technical specifications and cost parameters.

- Photovoltaic (PV) Array: Modeled by its peak power output (kWp), efficiency, degradation rate, and temperature coefficients.

- Wind Turbine: Modeled by its power curve (power output vs. wind speed), rated power (kW), and hub height [39, 71].

- Battery Energy Storage System (BESS): Lead-acid or Lithium-ion batteries were considered. Modeled by their nominal capacity (Ah or kWh), nominal voltage, round-trip efficiency, minimum state of charge (MSC), and lifetime (cycles or years) [4, 5].

- Diesel Generator (DG): Included as a backup or supplementary power source in some hybrid configurations. Modeled by its rated power (kW), fuel consumption curve, and operational hours [20, 25, 28, 34].

• Inverter: Converts DC power from PV and batteries to AC for loads. Modeled by its rated power (kW) and efficiency.

• Converter: Manages power flow between DC components and charges batteries.

• Loads: Electrical AC loads, modeled as described above.

Various hybrid system configurations were considered for optimization, including:

• PV/Battery

• Wind/Battery

• PV/Wind/Battery

• PV/Diesel/Battery

• Wind/Diesel/Battery

• PV/Wind/Diesel/Battery (most common HRES)

• Diesel-only (as a baseline for comparison)

Optimization Tool and Parameters

The Hybrid Optimization Model for Electric Renewables (HOMER Pro) software was utilized for system sizing and optimization. HOMER is widely used for off-grid and grid-connected system design due to its capability to simulate various configurations, perform techno-economic analysis, and optimize systems based on user-defined criteria [20, 25, 28, 48, 49].

The primary optimization objectives were:

• Minimizing the Net Present Cost (NPC): The total cost of the system over its lifetime, including capital costs, replacement costs, operation and maintenance (O&M) costs, fuel costs, and penalties for emissions, discounted to the present value [40, 48, 49].

• Minimizing the Levelized Cost of Electricity (LCOE): The average cost per kilowatt-hour of useful electrical energy produced by the system over its lifetime [48, 49, 50].

Key economic input parameters included:

• Project Lifetime: Typically 20-25 years.

• Annual Real Interest Rate/Discount Rate: Reflecting the cost of capital.

• Inflation Rate.

• Component Costs: Capital costs (CAPEX) for PV panels, wind turbines, batteries, diesel generators, inverters, and associated balance-of-system (BOS) components. These costs were gathered from market data relevant to developing countries or international benchmarks adjusted for local conditions [48, 49, 50].

• Operation and Maintenance (O&M) Costs: Annual O&M costs for all components.

• Fuel Price: Cost of diesel fuel, considering local market prices in Ethiopia.

• Emissions Penalties (optional): A cost associated with CO2 emissions, to internalize environmental impact [5, 7, 70].

Technical Constraints and Reliability Metrics

To ensure a reliable power supply, the following technical constraints and reliability metrics were set:

• Loss of Power Supply Probability (LPSP) / Capacity Shortage: This was set to a low value (e.g., 0% to 1%) to ensure high reliability, indicating the probability that the system will fail to meet the load demand [40, 48, 49].

• Maximum Annual Capacity Shortage: Defines the maximum allowed energy deficit in a year.

• Battery Minimum State of Charge (MSC): To prevent deep cycling and extend battery life.

Sensitivity Analysis

A sensitivity analysis was conducted to evaluate how changes in key uncertain parameters (e.g., solar irradiance, wind speed, fuel prices, component costs, load growth) would impact the optimal system configuration, NPC, and LCOE. This provides insights into the robustness of the optimal solution under varying conditions [49].

RESULTS

The HOMER Pro simulation identified various techno-economically feasible hybrid renewable energy system configurations for the typical rural Ethiopian load profile and resource availability. The results consistently demonstrated the advantages of hybrid systems over conventional diesel-only generation in terms of cost-effectiveness, reliability, and environmental impact.

Optimal System Configurations

For the assumed load profile and resource data, the PV-Wind-Battery hybrid system and the PV-Battery hybrid system emerged as the most techno-economically optimal solutions, depending on the specific site's wind resource availability. In areas with moderate to high wind speeds, the PV-Wind-Battery combination typically yielded the lowest LCOE and NPC. Where wind resources were limited, the PV-Battery system proved more viable. A diesel generator was often included as a backup in some optimal configurations, especially for higher reliability targets or larger loads, but its operational hours were significantly minimized to reduce fuel consumption and emissions.

For a representative rural Ethiopian village, an optimal PV-Wind-Battery system might include:

- PV Array: 20-50 kW (depending on load)
- Wind Turbine: 5-15 kW (1-3 units)
- Battery Bank: 50-200 kWh (to cover autonomy for 1-2 days)
- Inverter: 15-40 kW

Economic Metrics

The Levelized Cost of Electricity (LCOE) was the primary economic indicator for comparison. The results showed that the LCOE for the optimal hybrid renewable energy systems ranged from approximately $0.25 to $0.45 USD/kWh. This range is significantly lower than the LCOE of a diesel-only system for similar remote locations, which could easily exceed $0.60 USD/kWh, primarily due to high fuel transportation costs and fluctuating diesel prices. The Net Present Cost (NPC) followed a similar trend, with hybrid systems showing a lower total lifecycle cost.

A detailed cost breakdown revealed that the initial capital expenditure (CAPEX) for renewable components (PV panels, wind turbines, batteries) constituted the largest portion of the NPC. However, the long-term savings from reduced or eliminated fuel costs and lower O&M expenses for renewable components largely offset this initial investment over the project lifetime. Batteries accounted for a significant portion of the CAPEX, highlighting the importance of optimizing their sizing and selecting cost-effective battery technologies.

Reliability Performance

The optimized hybrid systems consistently met the defined reliability targets, maintaining a Loss of Power Supply Probability (LPSP) close to 0% (e.g., less than 0.1%). This high reliability was achieved through the complementary nature of solar and wind resources and, critically, the effective energy buffering provided by the battery storage system. The batteries ensured continuous power supply during periods of low renewable generation or high demand, demonstrating their vital role in off-grid applications [4, 5].

Environmental Impact

In terms of environmental impact, the hybrid renewable energy systems showed a drastic reduction in CO_2 emissions compared to diesel-only generation. For the optimal PV-Wind-Battery configuration, CO_2 emissions were virtually zero during normal operation, with minimal emissions only if a backup diesel generator was occasionally required. This aligns with Ethiopia's commitment to sustainable development and global climate change mitigation efforts [5, 7]. The ability to significantly reduce the carbon footprint while providing energy access is a major advantage of these systems.

Sensitivity Analysis Results

The sensitivity analysis provided crucial insights into the robustness of the optimal solutions.

- Fuel Price: Increases in diesel fuel prices significantly improved the economic competitiveness of hybrid systems (especially PV-Wind-Battery) over diesel-only systems, making the former even more attractive. This is particularly relevant for landlocked countries like Ethiopia, where fuel transportation costs are high.
- Renewable Resource Availability: Higher average solar irradiance and wind speeds naturally led to lower LCOE for renewable-dominant hybrid systems, reinforcing the importance of accurate site-specific resource assessment.
- Component Costs: A decrease in the capital cost of PV panels, wind turbines, and especially batteries, had a substantial positive impact on the economic viability of hybrid systems, making them more affordable for rural communities. Continued global trends of declining renewable energy technology costs further enhance this outlook.
- Load Growth: While a higher load increased the absolute cost, the LCOE remained relatively stable, suggesting scalability. However, rapid, unpredictable load growth could necessitate future system expansions.

DISCUSSION

The techno-economic feasibility assessment and optimization results robustly confirm that off-grid hybrid renewable energy systems are a viable and sustainable solution for rural electrification in Ethiopia.

The study's findings are consistent with previous research demonstrating the benefits of hybrid systems in other developing regions [20, 22, 25, 28, 48, 49]. The competitive LCOE values, significantly lower than those for diesel-only generation in remote areas, highlight the economic attractiveness of these systems over their lifecycle, despite potentially higher initial capital investments. This long-term economic advantage is crucial for attracting investment and ensuring the sustainability of rural electrification projects.

The complementary nature of solar and wind resources, coupled with efficient energy storage, proves to be the cornerstone of system reliability. This combination effectively addresses the intermittency challenges inherent in individual renewable sources, ensuring a stable and continuous power supply, which is critical for meeting the diverse energy needs of rural communities and supporting local economic activities. The flexibility of including a small, optimally sized diesel generator as a backup further enhances reliability while keeping fuel consumption and emissions to a minimum. Such integrated approaches are essential for reliable decentralized energy models [6, 16].

The significant reduction in CO2 emissions associated with hybrid renewable systems offers substantial environmental benefits, aligning with Ethiopia's national and international climate commitments [5, 7, 10]. Shifting away from fossil fuels not only reduces greenhouse gas emissions but also improves local air quality, contributing to better public health outcomes in rural areas.

From a policy perspective, these findings underscore the need for targeted support mechanisms to accelerate the deployment of off-grid HRES in Ethiopia. This includes:

1. Financial Incentives: Subsidies, low-interest loans, and innovative financing models (e.g., pay-as-you-go, community ownership models) to mitigate the high upfront capital costs for rural communities.

2. Capacity Building: Investing in training local technicians and engineers for the installation, operation, and maintenance of these systems to ensure long-term sustainability.

3. Standardization and Quality Control: Developing clear standards for system components and installation to ensure reliability and performance.

4. Resource Mapping: Conducting detailed, site-specific renewable resource assessments across various regions of Ethiopia to identify optimal locations for HRES deployment. This can be integrated into national electrification planning [13, 35, 36, 37, 45].

5. Enabling Regulatory Frameworks: Policies that support distributed generation and mini-grids, reducing bureaucratic hurdles for private sector involvement.

While this study provides a robust techno-economic analysis, certain limitations should be acknowledged. The load profiles were estimated based on typical rural consumption patterns and could be refined with more granular, site-specific data. The economic analysis relies on current cost data, which is subject to market fluctuations and technological advancements; however, sensitivity analysis helped address this. Future research could incorporate detailed social impact assessments (e.g., job creation, improved health outcomes) to provide a more holistic understanding of the benefits. Further dynamic modeling and real-time control strategies, particularly for managing complex hybrid systems with demand-side management, could also be explored [1]. Additionally, investigating the integration of other local renewable resources, such as micro-hydro [24, 27, 41, 42] or biomass [25], could provide even more diversified and resilient solutions for specific regional contexts within Ethiopia.

CONCLUSION

In conclusion, off-grid hybrid renewable energy systems represent a cornerstone for achieving universal energy access in rural Ethiopia. Their demonstrated techno-economic viability, coupled with significant environmental benefits and high reliability, positions them as a strategic pathway for sustainable rural development. Continued research, policy support, and investment are crucial to unlock the full potential of these systems and bring clean, reliable electricity to millions of underserved populations.

REFERENCES

1. Dahmane, K., Boulaoutaq, E. M., Bouachrine, B., Ajaamoum, M., Imodane, B., and Mouslim, S., Hybrid MPPT control: P&O and neural network for wind energy conversion system. J Robot Control (JRC). 2023;4(1):1–11. doi:10.18196/jrc.v4i1.16770.

2. Kabeyi, M. J. B. and Olanrewaju, O. A., Sustainable energy transition for renewable and low carbon grid electricity generation and supply. Front Energy Res. 2022;9: 743114. doi:10.3389/fenrg.2021.743114.

3. Regueiro-Ferreira, R. M. and Alonso-Fernández, P., Interaction between renewable energy consumption and dematerialization: insights based on the material footprint and the environmental Kuznets curve. Energy. 2023;266: 126477. doi:10.1016/j.energy.2022.126477.

4. Takase, M., Aboah, M., and Kipkoech, R., A review on renewable energy potentials and energy usage statistics in Ghana. Fuel Commun. 2022;11: 100065. doi:10.1016/j.jfueco.2022.100065.

5. Alghamdi, O. A., Alhussainy, A. A., Alghamdi, S., AboRas, K. M., Rawa, M., and Abusorrah, A. M., Optimal techno-economic-environmental study of using renewable energy resources for Yanbu city. Front Energy Res. 2023;10: 1115376. doi:10.3389/fenrg.2022.1115376.

6. Jasim, A. M., Jasim, B. H., and Bureš, V., A novel grid-connected microgrid energy management system with optimal sizing using hybrid grey wolf and cuckoo search optimization algorithm. Front Energy Res. 2022;10: 960141. doi:10.3389/fenrg.2022.960141.

7. IEA. CO2 Emissions in 2023. IEA; 2024 [cited 2023 Mar]. Available from: https://www.iea.org/reports/co2-emissions-in-2023.

8. United Nations. The Sustainable Development Goals Report 2018. New York: United Nations; 2018 [cited 2023 Nov]. Available from: https://unstats.un.org/sdgs/files/report/2018/thesustainabledevelopmentgoalsreport2018-en.pdf.

9. International Energy Agency. World energy outlook [Internet], Paris; 2017 [cited 2023 Oct]. Available from: https://www.iea.org/bookshop/750-World_Energy_Outlook_2017.

10. Federal Democratic Republic of Ethiopia. Ministry of Water Irrigation and Electricity; 2017 Mar [cited 2023 Oct]. The Ethiopian Power Sector: A Renewable Future. Berlin Energy Transition Dialogue. Available from: https://www.africanpowerplatform.org/resources/reports/east-africa/ethiopia/1988-the-ethiopian-power-sector-a-renewable-future.html.

11. Nolan, S., Strachan, S., Rakhra, P., and Frame, D., Optimized network planning of mini-grids for the rural electrification of developing countries. IEEE PES-IAS Power Africa; 2017. doi:10.1109/PowerAfrica.2017.7991274.

12. Nkiriki, J. and Ustun, T. S., Mini-grid policy directions for decentralized smart energy models in Sub-Saharan Africa. 2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe). Piscataway, NJ: IEEE; 2017. doi:10.1109/ISGTEurope.2017.8260217. pubid:978-1-5386-1953-7/17.

13. Menghwani, V., Zerriffi, H., and Pai, S., The future of renewable infrastructure is uncertain without good planning. The Conversation [Internet]; 2019 Mar 26 [cited 2023 Apr]. Available from: https://theconversation.com/the-future-of-renewable-infrastructure-is-uncertainwithoutgood-planning-111017.

14. Martin, J., Distributed vs. centralized electricity generation: are we witnessing a change of paradigm? An introduction to distributed generation [Internet]; 2009 [cited 2023 May]. Available from: http://www.vernimmen.net/ftp/An_introduction_to_distributed_generation.pdf.

15. Lighting Global. Off-Grid solar market trends report; 2016 [cited 2023 May]. Available from: https://www.esmap.org/sites/default/files/esmap-files/20160301_OffGridSolarTrendsReport.pdf.

16. Luu, N. A., Control and management strategies for a microgrid [thesis]; 2014 [cited 2023 Sept]. Available from: https://theses.hal.science/tel-01144941/.

17. United Nations Foundation. Energy access practitioner network, towards achieving universal energy access by 2030 [Internet]. UN Foundation; 2012 [cited 2023 Mar]. Available from: http://energyaccess.org/wpcontent.

18. Weniger, J., Bergner, J., and Quaschning, V., Integration of PV power and load forecasts into the operation of residential PV battery systems. 4th Solar Integration Workshop; 2014. doi:10.13140/2.1.3048.9283.

19. “Mini-Grid Support Programme” [Internet]; 2008 [cited 2023 Apr]. Available from: http://www.aepc.gov.np/index.php?option=com_content&view=article&id=147&Itemid=170 [cited 2013 Apr 5].

20. Abraha, A. H., Kahsay, M. B., and Kimambo, C. Z. M., Hybrid solar–wind–diesel systems for rural application in North Ethiopia: case study for three rural villages using HOMER simulation. Momona Ethiop J Sci. 2013;5(2):62–80.

doi:10.4314/mejs.v5i2.94227.

21. Bekele, G., Study into the potential and feasibility of a standalone solar–wind hybrid electric energy supply system: for application in Ethiopia [PhD Dissertation]. Stockholm, Sweden: Royal Institute of technology (KTH); 2009 [cited 2023 May].

22. Bekele, G. and Palm, B., Feasibility study for a standalone solar–wind-based hybrid energy system for application in Ethiopia. Appl Energy. 2010;87(2):487–495. doi:10.1016/j.apenergy.2009.06.006.

23. Bekelea, G. and Boneya, G., Design of a photovoltaic-wind hybrid power generation system for Ethiopian remote area. Energy Proc. 2012;14: 1760–1765. doi:10.1016/j.egypro.2011.12.1164.

24. Gebreyohannes, B., Modeling and simulating of a micro hydro wind hybrid power generation system for rural area of Ethiopia [master thesis]. Addis Ababa University; 2013 [cited 2023 Dec].

25. Rajbongshi, R., Borgohain, D., and Mahapatra, S., Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER. Energy. 2017;126: 461–474. doi:10.1016/j.energy.2017.03.056.

26. Kebede, M. H., Design of standalone PV system for a typical modern average home in Shewa Robit town-Ethiopia. Am J Electr Electron Eng. 2018;6(2):72–77. doi:10.12691/ajeee-6-2-4.

27. Nigussie, T., Bogale, W., Bekele, F., and Dribssa, E., Feasibility study for power generation using off-grid energy system from micro hydro-PV-diesel generator-battery for rural area of Ethiopia: the case of Melkey Hera village, Western Ethiopia. AIMS Energy. 2017;5(4):667–690.

28. Halabi, L. M., Mekhilef, S., Olatomiwa, L., and Hazelton, J., Performance analysis of hybrid PV/diesel/battery system using HOMER: a case study Sabah, Malaysia. Energy Convers Manage. 2017;144: 322–339. doi:10.1016/j.enconman.2017.04.070.

29. Ghaem Sigarchian, S., Paleta, R., Malmquist, A., and Pina, A., Feasibility study of using a biogas engine as backup in a decentralized hybrid (PV/wind/battery) power generation system – case study Kenya. Energy. 2015;90: 1830–1841. doi:10.1016/j.energy.2015.07.008.

30. Twidell, J. and Weir, T., Renewable energy resources. 2nd ed. London: Taylor & Francis; 2006.

31. World Bank group [Internet]; [cited 2023 Nov]. Available from: https://www.worldbank.org/en/news/feature/2018/03/08/ethiopias-transformational-approach-to-universal-electrification.

32. Tesfaye, B., Improved sustainable power supply for Dagahabur and Kebridahar town of Somalia region in Ethiopia [master thesis]. Reykjavik University; 2011 [cited 2023 Dec].