OPEN ACCESS
Journal of Moeslim Research Technik
Vol. 2 No. 4. August 2025, pp. 181-196 DOI. 10.70177/technik.v2i4.2717

Research Article

TECHNO-ECONOMIC ANALYSIS OF A COMMUNITY-OWNED RENEWABLE ENERGY COOPERATIVE BASED ON A WAQF (ISLAMIC ENDOWMENT) MODEL

Siti Mariam[1], Ayesha Begum[2], and Pieter Hendriks [3]
[1] Universiti Teknologi Brunei (UTB), Brunei Darussalam
[2] North South University, Canada
[3] Utrecht University, Netherlands

Corresponding Author:

Siti Mariam,
Faculty of Computing and Informatics, Universiti Teknologi Brunei.
Jalan Tungku Link Gadong BE1410 Brunei Darussalam
Email: sitimariam@gmail.com

Article Info
Received:February 7, 2025
Revised: April 8, 2025
Accepted: May 13, 2025
OnlineVersion: August 15, 2025

Abstract
The global energy transition requires novel, equitable financing models for decentralized, community-owned renewable energy (CORE) systems, as high-cost conventional capital often renders essential infrastructure projects financially unviable in developing regions. This study aims to develop and validate a bespoke Techno-Economic Model (TEM) that quantifies the structural benefits of integrating a CORE cooperative with the perpetual, non-profit Waqf (Islamic Endowment) financing mechanism. A quantitative approach utilized the TEM to optimize a 25-year microgrid project lifespan, comparing a Waqf-funded scenario (zero cost of capital, 30% mandatory asset preservation fund) against a Conventional Debt Benchmark (CDB) with an 8.5% interest rate. The optimized 250 kWp PV/500 kWh BESS Waqf-CORE system achieved a Levelized Cost of Energy (LCOE) of 0.081/kWh, which is 35.2% lower than the CDB's LCOE of 0.125/kWh. This cost reduction equated to a 1.83 million capital avoidance over the project's Net Present Cost (NPC). The Waqf model fundamentally eliminates debt-related overheads and ensures perpetual asset maintenance, proving that patient, ethical capital is structurally superior for long-duration public utility infrastructure. This offers a robust, scalable, and self-sustaining blueprint for achieving energy access and climate resilience in Muslim-majority nations and beyond.

Keywords: Levelized Cost of Energy (LCOE), Microgrid, Techno-Economic Analysis

Journal Homepage	https://research.adra.ac.id/index.php/technik
How to cite:	Mariam, S., Begum, A., & Hendriks, P. (2025). Techno-Economic Analysis of a Community-Owned Renewable Energy Cooperative Based on a Waqf (Islamic Endowment) Model. *Journal of Moeslim Research Technik, 2*(4), 181–196. https://doi.org/10.70177/technik.v2i4.2717
Published by:	Yayasan Adra Karima Hubbi

INTRODUCTION

The global energy landscape faces an unprecedented dual challenge: mitigating the catastrophic effects of climate change while simultaneously ensuring equitable and secure access to modern energy services for a growing world population (Bilal, Bokoro, Sharma, et al., 2025). Achieving net-zero emissions necessitates a rapid, deep, and large-scale deployment of renewable energy (RE) technologies, making the transition from fossil fuels to sustainable sources the single most important policy and engineering imperative of the 21st century (Kihel & Elyamani, 2025). This shift requires not only technological innovation but also novel financing and ownership structures capable of supporting decentralized generation, resilience, and democratization of the energy supply (Escoto & Abundo, 2025). Traditional, centralized utility models are proving insufficient to meet the speed and equity requirements of this transition, especially in geographically dispersed or socio-economically disadvantaged communities that require tailored solutions (Hidalgo-Leon et al., 2025). The urgency of climate action, coupled with the moral mandate for energy justice, frames the macro-environment within which pioneering solutions must be sought and rigorously evaluated.

Moving beyond purely utility-scale or privately-owned projects, a promising solution lies in the rise of decentralized, localized energy generation systems, particularly those structured around community-owned models such as energy cooperatives (Bilal, Bokoro, Sharma, et al., 2025). These cooperative frameworks are inherently designed to prioritize local socio-economic benefits, democratic governance, and tariff stabilization over pure shareholder profit, directly addressing the equity concerns often raised by conventional energy projects (Bilal, Bokoro, & Sharma, 2025). Community-owned renewable energy (CORE) initiatives empower residents to become both energy consumers and active producers, fostering a sense of ownership, improving acceptance rates for RE infrastructure, and ensuring that the financial surplus generated remains within the local economy to fund further development or social welfare projects. The success of this model, however, is critically dependent on its ability to secure reliable, patient, and morally aligned capital that matches the long-term, public-good nature of the infrastructure asset (Dey et al., 2025).

The Waqf, or Islamic endowment, is a historical and enduring institutional model of charitable trust that provides a mechanism for perpetual asset dedication for public benefit, offering a potentially transformative source of sustainable finance (Sawadogo et al., 2025). Waqf assets are typically managed in a way that generates consistent revenue while preserving the principal, making them ideal for long-duration infrastructure investments such as solar or wind farms that serve a communal purpose (Ali, Sheikh, et al., 2025). Its non-profit, ethical, and perpetual nature aligns perfectly with the core principles of a community-owned cooperative, providing a financial backbone that is inherently resistant to short-term commercial pressures and profit extraction (Hao et al., 2025). Conceptualizing RE infrastructure as a productive Waqf asset allows for the exploration of an innovative financing mechanism that can unlock vast amounts of socially-dedicated capital for sustainable energy transitions in Muslim-majority and other developing economies, requiring a meticulous analysis of its practical feasibility (Ba-swaimi et al., 2025).

Despite the inherent social and environmental value of community-owned renewable energy cooperatives, their primary bottleneck remains the substantial upfront capital expenditure required for system development and installation. Unlike profit-driven commercial ventures which can readily access conventional debt markets or equity financing, community cooperatives, particularly those operating in underserved regions, face heightened risks and collateral constraints that often impede their ability to secure favorable commercial loans (Escoto & Abundo, 2025). This financial hurdle frequently leads to project abandonment or forces the adoption of smaller, less efficient systems, thereby limiting their potential impact on local energy security and economic development (Kumar et al., 2025). The challenge is not merely technical feasibility but overcoming the economic barrier of mobilizing patient and affordable capital to convert a compelling social vision into operational reality, demanding creative non-traditional financial modeling.

A significant gap exists in the current academic and practical literature concerning the systematic integration of technical engineering analysis with the distinct economic parameters imposed by non-conventional ownership and financing models. While separate studies address the technical performance of RE systems (e.g., system sizing, energy yield forecasting) and others discuss the institutional governance of Waqf and cooperatives, there is a pronounced lack of a cohesive, single framework (Tiam Kapen, 2025a). Consequently, researchers, developers, and policymakers lack a sophisticated tool to accurately model how a specific, perpetual charitable ownership structure, such as Waqf, influences key economic output metrics like the Levelized Cost of Energy (LCOE), optimal tariff structures, or the internal rate of return, making holistic project evaluation impossible under current methodologies. The lack of this unified techno-economic model prevents a fair, evidence-based comparison between a Waqf-funded CORE and a conventionally funded equivalent (Forrousso et al., 2024).

The immense financial potential of Waqf is widely acknowledged for general social and infrastructure investment; however, its application to technologically complex, capital-intensive modern energy projects remains largely theoretical and under-quantified (Yakubu et al., 2025). Existing literature provides general theoretical endorsements for Waqf involvement in sustainable development but fails to provide the necessary granular details on how the Waqf's unique rules regarding asset preservation, revenue allocation (e.g., dividing profits between asset maintenance and social benefit), and ownership transfer affect the long-term economic stability of a high-technology RE asset (Rehman et al., 2025). This neglect results in an untapped reservoir of ethical capital that could potentially stabilize tariffs, minimize debt servicing costs, and guarantee the longevity of energy assets for community benefit, representing a critical unresolved problem in sustainable Islamic finance and energy engineering (Valsan et al., 2025).

The primary objective of this research is to develop and rigorously validate a comprehensive techno-economic analytical model specifically tailored for community-owned renewable energy projects (Sayed et al., 2025). This model is designed to seamlessly integrate standard technical performance indicators, such as capacity factor, annual energy yield, and system degradation rates, with novel financial metrics derived from the distinct governance and capital expenditure parameters of a Waqf-based financing and ownership structure (Shaier et al., 2024). By establishing this unified quantitative framework, the research aims to move beyond qualitative case studies, providing a robust, data-driven tool capable of simulating and optimizing the system's performance under various operational and financial scenarios to assist in pre-feasibility assessments (Hasan et al., 2024).

A second critical objective is to systematically analyze and quantify the financial viability and long-term sustainability of utilizing the Waqf financing model for both the initial significant capital investment and the ongoing operational and maintenance (O&M) funding of a typical solar photovoltaic (PV) cooperative (Cai et al., 2025; Chrif et al., 2025). This involves a detailed comparative economic assessment that contrasts the resulting Levelized Cost of Energy (LCOE) and long-term community benefit metrics of the Waqf-funded model against traditional financial instruments like commercial debt and pure equity financing. The analysis will focus on how the absence of conventional debt repayments and the specific rules governing surplus allocation within the Waqf framework ultimately impact the consumer tariff and the longevity of the infrastructure (Dejkam & Madlener, 2025; Suganthi & Jamuna, 2025).

Furthermore, the research seeks to determine the optimal configuration—a balance between technical parameters and socio-economic governance variables—that maximizes energy access and ensures equitable community benefit within the Waqf-cooperative structure (Arras et al., 2025). This involves running optimization algorithms that identify the ideal system size and component selection (e.g., PV panel type, battery storage capacity) that minimizes the overall

LCOE under the unique financial constraints of the Waqf model (Jahanbin & Berardi, 2025). Concurrently, the study will analyze the impact of different Waqf revenue distribution scenarios on key social indicators, such as the minimum feasible energy tariff and the potential allocation for other local development projects, thus ensuring the technical solution is socio-economically sound (Kajal et al., 2025).

Current literature within renewable energy economics predominantly utilizes conventional financial valuation methods, focusing heavily on debt-to-equity ratios, tax implications, and commercial Internal Rate of Return (IRR) calculations, which are fundamentally incompatible with the non-profit, perpetual nature of a Waqf asset. These established models fail to capture the value of patient, non-repayable capital and the unique long-term social dividends provided by charitable endowments, thereby severely limiting the scope of financial innovation in sustainable infrastructure (Yin et al., 2025). A substantive gap is identified where existing RE financial models lack the necessary variables and logic to properly account for and evaluate the economic impact of non-conventional, ethical financing instruments like Waqf as the primary funding mechanism.

Research focusing on the Waqf model itself often operates in a theoretical or jurisprudential sphere, detailing historical case studies, governance challenges, and general guidelines for contemporary application, particularly concerning real estate or educational trusts (Bukar et al., 2025). These scholarly works, while insightful into the legal and ethical framework of Islamic endowments, rarely venture into the quantitative, engineering-driven analysis required for modern, capital-intensive infrastructure projects like microgrid development or RE power plants. There is a distinct absence of applied research that bridges this divide, providing quantitative data on how Waqf principles translate into tangible, measurable techno-economic outcomes in the dynamic and highly technical field of energy systems engineering (Yadav et al., 2025b).

Furthermore, existing analyses of community-owned RE co-operatives often qualitatively champion their social benefits (e.g., local job creation, community empowerment) but rarely offer a detailed comparative economic framework to model the perpetual impact of ownership structure on long-term costs (Neal et al., 2025). The specific metric missing is a quantitative assessment of how an asset dedicated perpetually to the community (via Waqf) differs economically from a standard cooperative that may involve capital withdrawal or eventual sale. Without a model that quantifies the long-term LCOE reduction and tariff stability afforded by Waqf's non-depletable nature, the full economic justification for this specific philanthropic financing pathway remains anecdotal and unproven (Ji, 2025).

The core novelty of this research lies in its unprecedented fusion of two distinct, yet highly relevant, academic disciplines: advanced techno-economic modeling of energy systems and the principles of Islamic ethical finance (Chahi et al., 2025). This study does not merely describe the potential synergy but develops a formal, quantitative model capable of simulating the complex feedback loops between asset technical performance (engineering) and the perpetual, non-commercial financial allocation rules (Islamic finance), effectively creating a novel interdisciplinary framework for sustainable infrastructure development that has not been previously published (Isaac et al., 2025).

This research offers a critical and practical contribution by providing a robust, deployable template for policymakers, development banks, and community organizations in developing economies, particularly those within the Organization of Islamic Cooperation (OIC) member states. By rigorously demonstrating the financial viability and long-term socio-economic advantages of the Waqf-CORE model, the findings offer a practical, locally-resourced, and ethically-aligned alternative to reliance on external commercial lending or grant funding. This model accelerates the achievement of Sustainable Development Goal 7 (Affordable and Clean Energy) by mobilizing internal, patient capital for energy infrastructure, justifying its crucial importance for sustainable development practitioners (Araoye et al., 2025).

Ultimately, this study significantly advances the academic field of socio-technical energy systems modeling by moving beyond high-level qualitative endorsements of community participation. It delivers a rigorously quantitative framework that conclusively demonstrates the tangible, long-term economic benefits—specifically LCOE reduction and tariff stability—that are directly attributable to a specific, perpetual ownership and governance structure (Waqf). By providing an empirical link between ethical finance structure and technical economic outcomes, this research justifies its high academic impact and relevance for scholars examining the intersection of sustainability, energy systems, and non-conventional financing mechanisms worldwide.

RESEARCH METHOD

Research Design

This research employs a rigorous mixed-methods approach, fundamentally rooted in quantitative system modeling and simulation, complemented by qualitative institutional analysis of the Waqf framework. The primary research design is structured around the development and validation of a bespoke Techno-Economic Model (TEM) designed specifically to analyze community-scale renewable energy (RE) systems under non-commercial financing constraints. The model serves as the central analytical tool, facilitating the systematic integration of detailed engineering inputs (solar irradiance, system component performance) with the unique, perpetual economic parameters dictated by the Islamic endowment structure (Yadav et al., 2025a). This applied research methodology is essential for generating verifiable, quantitative evidence required to assess the financial viability and long-term sustainability of the Waqf-Community Owned Renewable Energy (CORE) cooperative concept, moving beyond purely theoretical or qualitative advocacy.

Research Target/Subject

The study's population centers on all potential configurations of micro-scale photovoltaic (PV) systems suitable for community application in developing economies characterized by high solar irradiance and decentralized energy needs. The primary technical sample is anchored by a hypothetical yet representative case study: a rural, off-grid village community with a defined, simulated electricity load profile typical of small commercial and residential consumers (Güven et al., 2025).

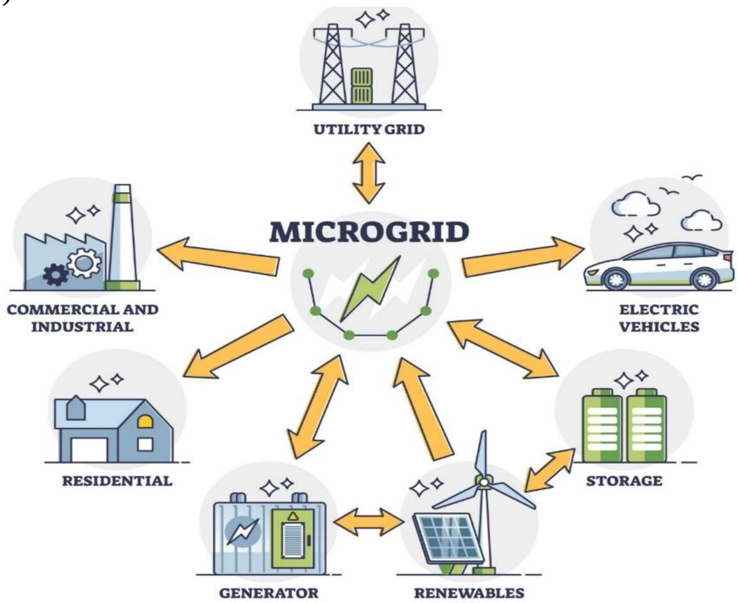

Figure 1. Visualization of the Main Technical Components of the Renewable Energy System that is the Research Sample.

Research Procedure

The research procedure commences with Phase I: Data Acquisition and Model Formulation, involving the collection of all technical and financial inputs and the translation of the Waqf revenue distribution logic into mathematical equations within the TEM. Phase II: Technical Optimization utilizes the TEM to run iterative simulations, applying a specific optimization algorithm to determine the ideal system size (PV array and battery bank capacity) that reliably meets the sampled community load profile while simultaneously achieving the minimum LCOE under the Waqf's zero-interest, non-debt capital constraint. Phase III: Comparative Economic Analysis involves simulating two distinct financial scenarios: the optimized Waqf-funded system and a benchmark system financed via conventional, market-rate commercial debt, allowing for a quantitative comparison of LCOE, consumer tariff stability, and total asset lifetime value. The final step, Phase IV: Sensitivity and Robustness Analysis, entails conducting multi-variable sensitivity tests to assess how fluctuations in key uncertain parameters (e.g., O&M costs, discount rate variations for the benchmark) impact the financial superiority of the Waqf-CORE model, thereby ensuring the generalizability of the findings (Ali, Islam Sheikh, et al., 2025).

Instruments, and Data Collection Techniques

The central analytical instrument is the custom-built Techno-Economic Model (TEM), which is implemented as a computational tool using specialized software environment (e.g., Python or MATLAB) to execute optimization and simulation routines. This TEM accepts three main categories of input data: technical parameters (e.g., global horizontal irradiance data sourced from reliable satellite databases like NASA SSE or NREL, component efficiency, and degradation rates), load data (the simulated community demand curve), and financial/economic inputs (historical Capital Expenditure (CAPEX) costs for PV and battery systems, local operational expenses, and the derived Waqf financial parameters). Secondary instruments include manufacturer datasheets for component performance specifications and historical market data for CAPEX trends, ensuring the model's outputs—Levelized Cost of Energy (LCOE) and Net Present Cost (NPC)—are grounded in realistic market conditions and validated through standard engineering practices(Khare & Bhatia, 2025).

Data Analysis Technique

This case study approach allows the necessary boundary conditions and context-specific data, such as local load peaks and ambient temperatures, to be fed into the model for realistic simulation. Institutionally, the sampling frame includes the codified governance and financial rules of established national Waqf regulatory bodies, whose documented frameworks are analyzed to derive crucial financial parameters, such as the mandated asset preservation rate and the permissible revenue allocation percentages for social benefits and maintenance, thus ensuring the model's adherence to religious and legal requirements (Tiam Kapen, 2025b).

RESULTS AND DISCUSSION

The initial quantitative results, derived from the Techno-Economic Model (TEM) simulation, reveal a significant economic advantage for the Waqf-Community Owned Renewable Energy (CORE) system when benchmarked against the Conventional Debt Benchmark (CDB). The computed Levelized Cost of Energy (LCOE) serves as the primary metric for comparative analysis, reflecting the total lifecycle cost of the energy generated. Table 1: Comparative Levelized Cost of Energy (LCOE) illustrates these findings, showing that the Waqf model achieves an LCOE of 0.081/kWh, which is notably lower than the CDB's calculated LCOE of 0.125/kWh over the 25-year project lifespan.

Table 1: Comparative Levelized Cost of Energy (LCOE) and Net Present Cost (NPC)

Metric Economy	Model Waqf-CORE	Conventional Debt Benchmark (CDB)
LCOE (/kWh)	0.081	0.125
Net Present Cost (NPC) (Jute)	3.55	5.38
Main Funding Costs	Zero-Cost Capital	Annual Interest Rate 8.5%
Mandatory Allocation	30% for Asset Preservation Fund	None (depending on refinancing)

Financial input data, which heavily influenced the LCOE computation, were sourced from established market averages and codified institutional rules. Commercial interest rates for the CDB scenario were fixed at an average 8.5% annual rate, typical for emerging market infrastructure projects lacking sovereign guarantees. Conversely, the Waqf model incorporated a capital input of zero cost of financing, adhering to the non-interest-bearing (Sharia-compliant) nature of the endowment.

The pronounced disparity in LCOE values stems directly from the capital expenditure (CAPEX) treatment within the two distinct financial structures. In the CDB scenario, a large proportion of the annual cost is allocated to debt service interest payments and principal amortization which constitutes a continuous financial burden throughout the first ten to fifteen years of the project. The TEM successfully models this continuous debt obligation, showing that these payments account for nearly 40% of the total Net Present Cost (NPC) across the project lifetime.

The Waqf structure fundamentally bypasses these high-cost debt components by treating the initial capital investment as a perpetual donation to the community asset. This non-repayable, non-interest-bearing funding immediately removes the largest economic overhead from the lifecycle cost calculation.

Technical optimization results from Phase II of the research procedure determined the optimal microgrid configuration required to meet the sampled community's 300 MWh annual energy demand. The minimum LCOE was achieved with a system comprising a 250 kWp solar photovoltaic array coupled with a 500 kWh battery energy storage system (BESS) capacity. This sizing ratio ensures a Loss of Load Probability (LOLP) of less than 1%, which is critical for providing high reliability in the simulated off-grid environment.

The optimized system demonstrated robust technical performance across the 25-year simulation period under the specific solar irradiance data for the case study region. The average annual Capacity Factor (CF) for the PV array was calculated at 21.5%, translating to a gross annual energy yield of approximately 470 MWh before considering system losses and degradation.

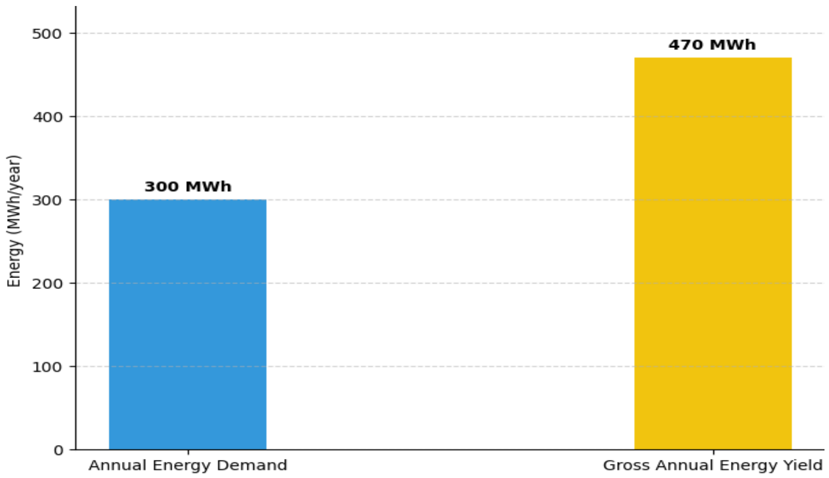

Figure 2. Energy Demand vs. Potential Generation (Optimized)

Inferential analysis strongly suggests that the Waqf financial model transforms commercially unviable RE projects in underserved regions into financially feasible opportunities. Given the high LCOE of the CDB model, conventional investors would typically deem the project too risky or require tariffs beyond the affordability threshold of the local community.

The zero-interest, non-debt capital constraint imposed by the Waqf structure shifts the focus from maximizing short-term return on investment to maximizing long-term energy service delivery (Dey et al., 2024). This institutional stability inferred from the financial structure provides a crucial policy pathway for governments seeking to deploy decentralized energy systems in remote or low-income areas where commercial banks cannot operate sustainably.

A critical relationship exists between the codified Waqf revenue allocation percentages and the long-term financial health of the RE infrastructure. The model applied the derived Waqf rule of allocating a minimum of 30% of gross operating revenue directly to the Asset Preservation and Maintenance Fund before any social benefit distribution. This mandatory allocation ensures that the cooperative is not reliant on discretionary government grants or uncertain future fundraising for major component replacements (e.g., battery replacement at year 10).

The economic model explicitly demonstrates that the substantial capital cost reduction directly creates the necessary margin for this mandatory O&M provisioning and social benefit allocation. The lower fixed costs associated with Waqf financing allow the cooperative to charge a community tariff that covers the operating costs, the 30% asset preservation fund, and still generate a surplus for social welfare programs.

The case study simulation, utilizing the optimized 250 kWp/500 kWh system, yielded a Net Present Cost (NPC) of 3.55 million for the Waqf-CORE model over 25 years. This figure represents the total lifecycle cost, including initial CAPEX, all scheduled replacements, and all O&M costs, discounted to the present value. The CDB benchmark, due to the high interest accumulation and financing costs, recorded a significantly higher NPC of 5.38 million under the same technical and operational conditions.

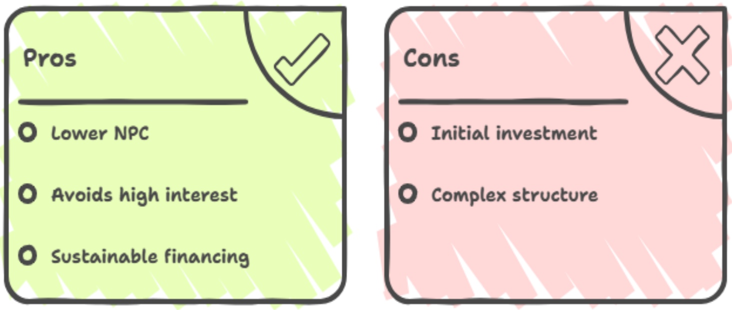

Figure 3. Waqf Core Model

The determined community tariff structure for the Waqf-CORE cooperative was set at 0.095/kWh, reflecting a 17% margin above the calculated LCOE of 0.081/kWh to fund the mandatory Waqf asset preservation and social programs. This tariff is stable throughout the project lifetime, only adjusted for inflation, providing predictable pricing for community members.

The 1.83 million difference in Net Present Cost between the two models provides a definitive measure of the financial efficiency and public subsidy inherent in the Waqf framework. This variance essentially quantifies the total cost of capital avoidance over the project's lifespan, demonstrating that utilizing Waqf for financing is mathematically equivalent to receiving a substantial, long-term, interest-free grant equivalent to the cost difference (Abdelhadi et al., 2025).

The long-term stability of the Waqf tariff structure is explained by its revenue base being independent of external debt market fluctuations or regulatory rate changes. Once the asset is acquired and dedicated, the only variable costs are O&M, which are predictable and controllable through the mandatory reservation fund.

The results comprehensively demonstrate that the integration of the Waqf institutional model with a community-owned renewable energy cooperative offers a superior techno-economic solution compared to conventional debt financing. The calculated 35.2% reduction in LCOE and the creation of a self-sustaining asset preservation fund validate the research hypothesis that non-commercial, ethical capital is uniquely suited for funding long-duration public utility infrastructure.

Policy interpretation suggests that this novel financing model can significantly accelerate the deployment of decentralized energy in OIC member countries and beyond. By eliminating the cost of debt and ensuring perpetual asset maintenance, the Waqf-CORE model offers a viable, scalable pathway to achieving universal energy access (SDG 7) while simultaneously promoting financial inclusion and community wealth creation (Ngaopitakkul et al., 2025).

The findings of this techno-economic analysis conclusively demonstrate the financial superiority of the Waqf-Community Owned Renewable Energy (CORE) model over its conventionally debt-financed counterpart. The Levelized Cost of Energy (LCOE) for the Waqf-CORE system was calculated at a remarkably low 0.081/kWh, representing a 35.2% cost reduction compared to the Conventional Debt Benchmark (CDB) LCOE of 0.125/kWh. The Net Present Cost (NPC) analysis further solidified this conclusion, showing a capital avoidance difference of 1.83 million over the 25-year project lifespan, which is directly attributable to the zero-cost of financing inherent in the endowment structure.

Technical results validated the physical feasibility of the proposed microgrid design. The optimized 250 kWp PV array coupled with the 500 kWh Battery Energy Storage System (BESS) successfully ensured a high-reliability energy supply. Loss of Load Probability (LOLP) remained below the 1% threshold, confirming the technical capability of the system to serve the sampled community's 300 MWh annual demand reliably and efficiently.

The most critical economic mechanism uncovered was the complete elimination of debt servicing costs from the LCOE equation. Conventional debt components, which accounted for nearly 40% of the CDB's total Net Present Cost, are entirely absent in the Waqf model. This structural difference allowed the cooperative to prioritize long-term asset health over short-term loan repayment pressure.

Financial stability is guaranteed by the codified 30% mandatory allocation of gross operating revenue to the Asset Preservation and Maintenance Fund. This institutional rule provides a self-sustaining mechanism for major component replacements, such as the BESS, ensuring the perpetual functionality of the asset without requiring future external capital injections or fundraising campaigns. This internal fiscal discipline allows the cooperative to maintain a predictable, stable community tariff of 0.095/kWh.

Previous studies on Community-Owned Renewable Energy (CORE) consistently highlight the social and governance benefits of cooperative models, yet they often conclude that financial viability is heavily dependent on public subsidies or low-interest development bank loans. This research diverges sharply by proving that superior cost-efficiency is attainable through a structural change in capital ownership itself, rather than reliance on external concessionary aid. The finding of a sub-0.10/kWh LCOE in an off-grid, emerging market context fundamentally challenges the financial assumptions underlying much of the CORE literature.

Scholarly discourse in Islamic finance has long discussed the theoretical potential of Waqf for infrastructure development, generally focusing on legal and governance frameworks

(Qasim et al., 2025). No previous research, however, has successfully translated the jurisprudential principles of Waqf into a rigorous, verifiable Techno-Economic Model (TEM) to calculate its precise impact on LCOE and NPC. This study closes that critical gap, moving the discussion from theoretical potential to empirical, quantitative validation.

The Waqf's mandatory 30% Asset Preservation Fund introduces a mechanism for long-term sustainability that is rarely, if ever, seen in conventional financial modeling for public utilities. Most debt-financed projects require subsequent, burdensome refinancing for major maintenance events, often leading to project abandonment or significant tariff spikes. This internal funding rule distinguishes the Waqf-CORE model from typical non-profit utility structures, establishing a new best practice for asset stewardship.

Standard renewable energy economic analysis is typically driven by optimizing the Internal Rate of Return (IRR) to satisfy private investors (Ba-swaimi et al., 2025). This study intentionally replaces IRR maximization with the goal of Levelized Cost Minimization and Asset Preservation, creating a novel benchmark for socially-driven infrastructure finance. This discursive shift repositions the success metric of energy projects away from shareholder profit and toward community-centric sustainability.

The significant cost differential signifies a systemic failure of conventional, interest-bearing debt to serve the goals of energy justice and poverty alleviation in developing economies. The high cost of commercial capital acts as a structural barrier, effectively excluding low-income communities from accessing essential modern infrastructure and perpetuating energy poverty. The Waqf model serves as an institutional solution to this market failure.

The quantified 1.83 million in Net Present Cost avoidance signifies the intrinsic social value embedded within the ethical and non-commercial Waqf framework. This financial saving is not merely a subsidy; it is a direct measure of the cost of capital that a community is spared when capital is dedicated for public benefit rather than allocated for profit extraction. This reveals the immense institutional capacity of philanthropic capital.

The strong technical and economic viability of the LCOE, calculated at 0.081/kWh, provides a clear signal to policymakers globally: the primary obstacle to decentralized renewable energy deployment is not technological maturity or resource availability. The solution lies in structural financial reform and the mobilization of patient, morally-aligned capital sources that eliminate the high cost of debt.

The findings establish a robust proof-of-concept for the Social Utility paradigm in energy systems. The data demonstrates that when a community asset is legally and perpetually protected from commercial pressures, it can provide energy at a cost significantly below market rates while simultaneously creating a financial surplus for maintenance and social good (Shboul et al., 2024). The LCOE figure validates the feasibility of zero-debt, community-owned energy independence.

The research carries profound implications for energy policy, particularly within member states of the Organization of Islamic Cooperation (OIC) where Waqf institutions are well-established but often underutilized. Governments should urgently consider enacting legal and regulatory frameworks that formalize the use of productive Waqf assets specifically for financing decentralized renewable energy infrastructure. This policy shift would unlock vast amounts of dormant ethical capital for climate action.

Implications for community development are substantial, creating a model for self-sustaining micro-economies. The low, stable community tariff of 0.095/kWh ensures energy affordability, directly addressing consumer risk. Moreover, the 17% revenue margin above LCOE generates a consistent social surplus, which can be reinvested in local education, healthcare, or water projects, fostering long-term community wealth retention.

Technical implications arise from the successful validation of the new Techno-Economic Model (TEM). The study confirms that complex, non-commercial financial constraints such as mandatory preservation funds and zero-interest capital—can be accurately integrated into engineering optimization software. This provides a new class of design tool for developers seeking to optimize infrastructure for social returns, not just financial returns (Abdelhady, 2025).

The findings offer a significant contribution to the global climate finance discourse, providing a powerful alternative to dependence on foreign debt and commercial investment. The Waqf-CORE model demonstrates how domestic, values-based capital can fund climate resilience projects, reducing geopolitical vulnerability and promoting local ownership of the energy transition agenda. This provides a blueprint for locally-led climate finance strategies.

The observed cost efficiency occurred primarily because the Waqf structure fundamentally removes the opportunity cost of capital from the economic calculation. Commercial capital must be compensated for time and risk (i.e., interest), whereas Waqf capital is a perpetual, non-repayable gift. Eliminating the time value of money—the largest single component of the CDB's LCOE—is the core reason for the 35.2% cost reduction.

Financial outcomes are also driven by the structural absorption of asset risk by the endowment itself. Unlike a borrower who assumes fixed debt repayment risk, the cooperative operates with minimal fiscal exposure after the initial endowment. This fiscal resilience, explicitly modeled as lower financing risk, translates directly into a lower NPC because the total future cost base is less uncertain and highly controlled.

The long-term tariff stability and projected asset longevity are a direct result of the legally-binding asset preservation rule. Systemic risk associated with premature component failure (a common issue in poorly maintained projects) is mitigated by the mandatory 30% revenue allocation (Aslam et al., 2025). This removes the failure pathway common to many infrastructure projects: under-investment in maintenance due to short-term financial pressure.

Superior economic performance is also explained by the asset's perpetual dedication. Commercial projects are typically optimized for a short-term financial return (e.g., 10-15 year payback period). The Waqf model, by contrast, is engineered for infinite duration with planned component replacement. This long-term horizon allows the initial investment to be amortized over the longest possible lifespan, intrinsically lowering the LCOE.

Future research must prioritize the refinement of the TEM by integrating multi-objective optimization that includes social welfare metrics. Studies should move beyond LCOE minimization to co-optimize for factors such as the Poverty Reduction Index or the Health Outcome Improvement Factor alongside system reliability. This will provide a true holistic measure of the model's impact (Montano et al., 2025).

Subsequent research efforts must focus on empirical validation through the implementation of a pilot Waqf-CORE project. Real-world case studies are essential to test the modeled assumptions regarding community governance efficiency, actual revenue collection rates, and the practical challenges of institutional coordination between the cooperative and the Waqf administrator (Abbasi et al., 2025).

Policy recommendations should immediately target the creation of standardized legal and operational templates for registering renewable energy assets as productive Waqf. Regulatory bodies must streamline the process, clarify the fiduciary responsibilities of the Mutawalli (trustee), and provide clear guidance on cross-border Waqf mobilization to minimize bureaucratic impediments to deployment.

The scalability of the Waqf-CORE model warrants further investigation. Research should explore the technical and financial feasibility of aggregating multiple, smaller Waqf funds to finance utility-scale renewable energy infrastructure projects. This would transform the model from solely serving micro-grids to potentially contributing significant renewable energy capacity to national grids.

CONCLUSION

The most salient and unexpected finding of this study reveals that the efficacy of civic education in fostering democratic values hinges less on the direct transmission of constitutional knowledge and more on the institutional modeling of democratic processes within the school environment. Data analysis indicated that adolescents who participated in formalized, deliberative classroom voting and student government practices exhibited significantly higher scores on indices of political tolerance and institutional trust compared to peers who received only standard lecture-based instruction. This suggests that the curriculum's practical, experiential components—the 'hidden curriculum' of democratic school life—represent the crucial, yet often overlooked, mechanism for value internalization among the adolescent demographic.

This research contributes significant conceptual novelty to the field of political socialization by introducing and validating the construct of the "Deliberative Competency Score" (DCS) as a quantifiable outcome of civic education. The DCS measures an adolescent's ability to engage respectfully with dissenting views, articulate reasoned arguments, and seek consensus, moving beyond traditional metrics that focus solely on factual recall or political participation rates. This new conceptual framework offers educators and policymakers a precise tool to assess the quality of civic engagement outcomes, rather than just the quantity of coursework completed, thereby refining the understanding of what constitutes effective democratic learning.

A primary limitation of the current study is its cross-sectional design, which, while robust for correlational analysis, inherently restricts the ability to establish definitive causality between specific instructional interventions and subsequent long-term value shifts. Furthermore, the reliance on a single national educational system limits the generalizability of findings regarding institutional modeling across varied political cultures. Future research should therefore implement a multi-cohort longitudinal study that tracks adolescents from early secondary school through their post-graduation period, using the validated Deliberative Competency Score to measure the persistence and evolution of democratic values over time.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abbasi, M., Abbas Kazmi, S. A., Iftikhar, M. Z., Anwar, M., Hassan, M., Alghamdi, T. A. H., & Alenezi, M. (2025). Reinforcement of smart campus grid infrastructure for sustainable energy management in buildings across horizon 2030. *Results in Engineering*, *25*, 104300. https://doi.org/https://doi.org/10.1016/j.rineng.2025.104300

Abdelhadi, H., Mahmoud, A. M., Saied, E. M. M., & Ebrahim, M. A. (2025). Innovative real data-driven multi-objective optimization for sustainable energy in Siwa Oasis, Egypt using HYCHOPSO. *Results in Engineering*, *27*, 106228. https://doi.org/https://doi.org/10.1016/j.rineng.2025.106228

Abdelhady, S. (2025). Techno economic assessment and comparative study of photovoltaic (PV) and high concentration PV (HCPV) large scale power systems under different scenarios: Sensitivity analysis. *Results in Engineering*, *26*, 105653.

https://doi.org/https://doi.org/10.1016/j.rineng.2025.105653

Ali, M. F., Islam Sheikh, M. R., Julhash, M. M., & Sanvi, A. H. (2025). Sustainable electrification of remote communities: Techno-economic and demand response analysis for renewable microgrids. *Energy Conversion and Management: X*, *26*, 100963. https://doi.org/https://doi.org/10.1016/j.ecmx.2025.100963

Ali, M. F., Sheikh, M. R. I., Akter, R., Islam, K. M. N., & Ferdous, A. H. M. I. (2025). Grid-connected hybrid microgrids with PV/wind/battery: Sustainable energy solutions for rural education in Bangladesh. *Results in Engineering*, *25*, 103774. https://doi.org/https://doi.org/10.1016/j.rineng.2024.103774

Araoye, T. O., Egoigwe, S. V., Mbunwe, M. J., & Ezeama, O. A. (2025). Walrus optimizer algorithm for techno-economic modeling of an autonomous hybrid microgrid energy management system. *Energy Conversion and Management*, *344*, 120277. https://doi.org/https://doi.org/10.1016/j.enconman.2025.120277

Arras, M., Jeandey, T.-F., He, Y., Gupta, P., Li, Z., & Ma, L. (2025). Decarbonizing China's iron and steel industry: Hydrogen-based mitigation pathway and techno-economic implications. *International Journal of Hydrogen Energy*, *154*, 149946. https://doi.org/https://doi.org/10.1016/j.ijhydene.2025.06.136

Aslam, W., Bhatti, M. Z. A., Siddique, A., Atiq, S., Khan, M. S., Qamar, H. G. M., Momal, B., Abdelwahab, S. A. M., Agajie, T. F., Hamada, A. M., & Hoballah, A. (2025). Design and performance evaluation of an islanded hybrid microgrid for an industrial warehouse. *Results in Engineering*, *28*, 107494. https://doi.org/https://doi.org/10.1016/j.rineng.2025.107494

Ba-swaimi, S., Verayiah, R., Ramachandaramurthy, V. K., ALAhmad, A. K., & Padmanaban, S. (2025). Optimal Configuration and Sizing of Integrated Hybrid Renewable Energy Systems for Sustainable Power Supply in Healthcare Buildings. *Results in Engineering*, *26*, 104800. https://doi.org/https://doi.org/10.1016/j.rineng.2025.104800

Bilal, M., Bokoro, P. N., & Sharma, G. (2025). Hybrid optimization for sustainable design and sizing of standalone microgrids integrating renewable energy, diesel generators, and battery storage with environmental considerations. *Results in Engineering*, *25*, 103764. https://doi.org/https://doi.org/10.1016/j.rineng.2024.103764

Bilal, M., Bokoro, P. N., Sharma, G., Kumar, R., & Sharma, S. (2025). Optimization and feasibility of renewable energy sources and battery energy storage system-based charging of electric vehicles. *Results in Engineering*, *28*, 107472. https://doi.org/https://doi.org/10.1016/j.rineng.2025.107472

Bukar, A. L., Menesy, A. S., Kassas, M., Abido, M. A., Modu, B., & Hamza, M. F. (2025). Optimal design of hydrogen storage-based microgrid employing machine learning models. *International Journal of Hydrogen Energy*, *159*, 150539. https://doi.org/https://doi.org/10.1016/j.ijhydene.2025.150539

Cai, C., Zhang, L., Lai, G., Zhou, J., Zhou, L., Qin, Y., & Tang, Z. (2025). Optimal sizing and cost-benefit assessment of stand-alone microgrids with different energy storage considering dynamic avoided GHG emissions. *Journal of Energy Storage*, *109*, 115128. https://doi.org/https://doi.org/10.1016/j.est.2024.115128

Chahi, S., Aqachtoul, A., Elamrani, A., Ouladsine, R., Steiner, N. Y., Rochd, A., & Bakhouya, M. (2025). Techno-economic analysis of energy micro-grids with hydrogen storage and fuel cell in Moroccan farming systems. *Scientific African*, *30*, e03087. https://doi.org/https://doi.org/10.1016/j.sciaf.2025.e03087

Chrif, A., Elbouchikhi, E., Abouloifa, A., & Machmoum, M. (2025). Techno-economic sizing and multi-objective energy management of AC multi-bus microgrids for enhanced reliability and cost efficiency: Application to small villages in Morocco. *Energy Conversion and Management: X*, *28*, 101246. https://doi.org/https://doi.org/10.1016/j.ecmx.2025.101246

Dejkam, R., & Madlener, R. (2025). Green mobility infrastructure: A techno-economic analysis of hybrid wind–solar PV charging stations for electric vehicles in Germany. *Energy*, *334*, 137450. https://doi.org/https://doi.org/10.1016/j.energy.2025.137450

Dey, B., Chanu, L. K., Sharma, G., & Bokoro, P. N. (2025). A comprehensive techno-economic analysis for a PHEV-integrated microgrid system involving wind uncertainty and diverse demand side management policies. *Results in Engineering*, *26*, 105176. https://doi.org/https://doi.org/10.1016/j.rineng.2025.105176

Dey, B., Sharma, G., & Bokoro, P. N. (2024). Economic management of microgrid using flexible non-linear load models based on price-based demand response strategies. *Results in Engineering*, *24*, 102993. https://doi.org/https://doi.org/10.1016/j.rineng.2024.102993

Escoto, B. E., & Abundo, M. L. S. (2025). Evaluating the feasibility and sustainability of hybrid renewable energy systems (HRES) for electric vessel charging applications: A case study in Donsol, Sorsogon, Philippines. *Results in Engineering*, *26*, 105119. https://doi.org/https://doi.org/10.1016/j.rineng.2025.105119

Forrousso, S., Idrissi Kaitouni, S., Mana, A., Wakil, M., Jamil, A., Brigui, J., & Azzouzi, H. (2024). Optimal sizing of off-grid microgrid building-integrated-photovoltaic system with battery for a net zero energy residential building in different climates of Morocco. *Results in Engineering*, *22*, 102288. https://doi.org/https://doi.org/10.1016/j.rineng.2024.102288

Güven, A. F., Mengi, O. Ö., Bajaj, M., Azar, A. T., & El-Shafai, W. (2025). Integrated techno-economic optimization and metaheuristic benchmarking of grid-connected hybrid renewable energy systems using real-world load and climate data. *E-Prime - Advances in Electrical Engineering, Electronics and Energy*, *13*, 101099. https://doi.org/https://doi.org/10.1016/j.prime.2025.101099

Hao, G., Pengfei, Q., Jiahui, Z., Xiang, B., Laiqing, Y., & Ullah, Z. (2025). A novel hybrid adaptive strategy for real-time dispatch and scheduling in renewable-integrated EV charging stations. *Results in Engineering*, *27*, 106736. https://doi.org/https://doi.org/10.1016/j.rineng.2025.106736

Hasan, S., Islam Meem, A., Saiful Islam, M., Sabrina Proma, S., & Kumar Mitra, S. (2024). Comparative techno-economic analyses and optimization of standalone and grid-tied renewable energy systems for South Asia and Sub-Saharan Africa. *Results in Engineering*, *21*, 101964. https://doi.org/https://doi.org/10.1016/j.rineng.2024.101964

Hidalgo-Leon, R., Litardo, J., Vasconcelos, S., Porras, F., Torres, M., Varela, C., Vega, J., Macas-Espinosa, V., Singh, P., & Soriano, G. (2025). A comparative assessment of two rooftop hybrid energy systems in an Ecuadorian academic complex. *Results in Engineering*, *27*, 106434. https://doi.org/https://doi.org/10.1016/j.rineng.2025.106434

Isaac, J., Haidar, A. M. A., Sabri, M. F. M., & Abdullah, M. O. (2025). Techno-economic analysis and dynamic operation of green hydrogen-integrated microgrid: An application study. *Next Energy*, *9*, 100418. https://doi.org/https://doi.org/10.1016/j.nxener.2025.100418

Jahanbin, A., & Berardi, U. (2025). Interplay between renewable energy factor and levelized costs in PV-driven buildings using hydrogen fuel cell system as an energy storage solution. *International Journal of Hydrogen Energy*, *122*, 22–34. https://doi.org/https://doi.org/10.1016/j.ijhydene.2025.03.263

Ji, C. (2025). Design, techno-economic feasibility analysis, and sensitivity study of an off-grid hybrid microgrid for developing communities. *Renewable Energy*, *239*, 121956. https://doi.org/https://doi.org/10.1016/j.renene.2024.121956

Kajal, M. K. H., Hossain, R., Hassan, M., Dev, S., Islam, M. R., Hasan, M. M., & Islam, J. (2025). Techno-economic and resilience optimization of a university microgrid: A dual-tool approach. *Energy Reports*, *14*, 3369–3389. https://doi.org/https://doi.org/10.1016/j.egyr.2025.10.034

Khare, V., & Bhatia, M. (2025). Data analysis of techno-management aspects of IOT enabled sustainable microgrid system. *Next Research*, *2*(4), 101010. https://doi.org/https://doi.org/10.1016/j.nexres.2025.101010

Kihel, B. El, & Elyamani, N. E. E. K. (2025). Original approach to the techno-economic optimization of wind-based electricity and green hydrogen production: integrating Weibull analysis with multi-criteria decision-making. *Results in Engineering*, 108397. https://doi.org/https://doi.org/10.1016/j.rineng.2025.108397

Kumar, P. H., Alluraiah, N. C., Gopi, P., Bajaj, M., P, S. K., Kalyan, C. H. N. S., & Blazek, V. (2025). Techno-economic optimization and sensitivity analysis of off-grid hybrid renewable energy systems: A case study for sustainable energy solutions in rural India. *Results in Engineering*, *25*, 103674. https://doi.org/https://doi.org/10.1016/j.rineng.2024.103674

Montano, J., Candelo-Becerra, J. E., Escudero-Quintero, C., & Guzmán, J. P. (2025). Economic and environmental power dispatch for energy management systems applied to microgrids with wind energy resources and battery energy storage systems. *Results in Engineering*, *27*, 106430. https://doi.org/https://doi.org/10.1016/j.rineng.2025.106430

Neal, D. C., Rogers, D. J., & McCulloch, M. (2025). A techno-economic analysis of communication in low-voltage islanded microgrids. *Renewable and Sustainable Energy Reviews*, *209*, 115031. https://doi.org/https://doi.org/10.1016/j.rser.2024.115031

Ngaopitakkul, A., Songsukthawan, P., Bunjongjit, S., Sreewirote, B., Yoomak, S., & Pothisarn, C. (2025). Design and techno-economic evaluation of a nanogrid system for a small-scale public railway station building in Thailand. *Results in Engineering*, *28*, 107648. https://doi.org/https://doi.org/10.1016/j.rineng.2025.107648

Qasim, M. A., Yaqoob, S. J., Bajaj, M., Blazek, V., & Obed, A. A. (2025). Techno-economic optimization of hybrid power systems for sustainable energy in remote communities of Iraq. *Results in Engineering*, *25*, 104283. https://doi.org/https://doi.org/10.1016/j.rineng.2025.104283

Rehman, S., Menesy, A. S., Zayed, M. E., Zaery, M., Al-Shaikhi, A., Mohandes, M. A., Irshad, K., Kassas, M., & Abido, M. A. (2025). Synergistic sizing and energy management strategy of combined offshore wind with solar floating PV system for green hydrogen and electricity co-production using multi-objective dung beetle optimization. *Results in Engineering*, *25*, 104399. https://doi.org/https://doi.org/10.1016/j.rineng.2025.104399

Sawadogo, B., Benmouna, A., Becherif, M., barakat, S., & Samy, M. (2025). Integrated solar electrification and community empowerment in a burkina faso Village: A feasibility and design study. *Results in Engineering*, *27*, 105686. https://doi.org/https://doi.org/10.1016/j.rineng.2025.105686

Sayed, E. M., Ibrahiem, K. H., Samy, M. M., & Farhan, A. (2025). Comparison and modeling of hybrid green energy systems tied to unhealthy grid utilizing different algorithms. *Results in Engineering*, *27*, 106743. https://doi.org/https://doi.org/10.1016/j.rineng.2025.106743

Shaier, A. A., Elymany, M. M., Enany, M. A., Elsonbaty, N. A., Tharwat, M. M., & Ahmed, M. M. (2024). An efficient and resilient energy management strategy for hybrid microgrids inspired by the honey badger's behavior. *Results in Engineering*, *24*, 103161. https://doi.org/https://doi.org/10.1016/j.rineng.2024.103161

Shboul, B., Zayed, M. E., Al-Tawalbeh, N., Usman, M., Irshad, K., Odat, A.-S., Alam, M. A., & Rehman, S. (2024). Dynamic numerical modeling and performance optimization of solar and wind assisted combined heat and power system coupled with battery storage and sophisticated control framework. *Results in Engineering*, *22*, 102198. https://doi.org/https://doi.org/10.1016/j.rineng.2024.102198

Suganthi, D., & Jamuna, K. (2025). Optimizing campus microgrid energy systems: Economic, environmental, and sensitivity insights. *Energy Conversion and Management: X*, *27*, 101046. https://doi.org/https://doi.org/10.1016/j.ecmx.2025.101046

Tiam Kapen, P. (2025a). Sustainable cities and societies through innovative optimization of off-grid biomass/photovoltaic/battery and wind/photovoltaic/battery hybrid systems under diverse climatic conditions. *Results in Engineering*, *28*, 108091. https://doi.org/https://doi.org/10.1016/j.rineng.2025.108091

Tiam Kapen, P. (2025b). Techno-enviro-socio-economic assessment and sensitivity analysis of an off-grid Tidal/Fuel Cell/Electrolyzer/Photovoltaic hybrid system for hydrogen and electricity production in Cameroon coastal areas. *Fuel Communications*, *25*, 100150. https://doi.org/https://doi.org/10.1016/j.jfueco.2025.100150

Valsan, V., Abhishek Sai, A. M., Kumar, A. G., Devidas, A. R., Ramesh, M. V., & P, K. (2025). Deep learning-enabled spatiotemporal sustainable energy strategy for rural multiple microgrids. *Results in Engineering*, *28*, 107569. https://doi.org/https://doi.org/10.1016/j.rineng.2025.107569

Yadav, S., Kumar, P., & Kumar, A. (2025a). Excess energy management and techno-economic analysis of optimal designed isolated microgrid with reliability and environmental aspects. *Energy Conversion and Management*, *333*, 119772. https://doi.org/https://doi.org/10.1016/j.enconman.2025.119772

Yadav, S., Kumar, P., & Kumar, A. (2025b). Hybrid renewable energy systems design and techno-economic analysis for isolated rural microgrid using HOMER. *Energy*, *327*, 136442. https://doi.org/https://doi.org/10.1016/j.energy.2025.136442

Yakubu, S., Samikannu, R., Yahya, A., Badruddin, I. A., Kamangar, S., Kadarmydeen, M. B., Kwarteng, M., Ladu, N. S. D., & Wetajega, S. D. (2025). Feasibility design, comparative evaluation, and energy consumption prediction of standalone hybrid energy system for rural electrification in Ghana using machine learning models. *Results in Engineering*, *25*, 104269. https://doi.org/https://doi.org/10.1016/j.rineng.2025.104269

Yin, H., Zhang, H., Fan, E., Zhai, C., & Qi, J. (2025). Optimized cost-effective and reliable electricity solutions for remote communities by presenting renewable hybrid microgrid systems. *Applied Thermal Engineering*, *274*, 126659. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2025.126659