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Design of an integrated biogas, biomass and solar bifacial renewable energy system for rural health facilities

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Abstract

This project focuses on designing and optimizing a resilience-oriented hybrid polygeneration system tailored to meet the specific energy needs of rural health facilities and teaching hospitals. Hospitals are prime candidates for integrated energy systems due to their continuous operation, consistent occupancy, and diverse energy requirements, which typically encompass electricity, steam for sterilization, domestic hot water, and chilled water for cooling. In rural areas, where grid reliability is often a significant concern, these facilities need decentralized, sustainable, and dependable energy sources to support critical operations, such as Intensive Care Units (ICUs) and Operating Rooms (ORs). The proposed system incorporates three key renewable technologies: Solar Bifacial Photovoltaics, Biomass Energy, and Biogas Systems. The project methodology utilizes Mixed-Integer Linear Programming (MILP) and Pinch Analysis to identify the optimal configuration and operational strategy. Optimization is approached from a TEESR (Technical, Economic, Environmental, Social, and Reliability) perspective, ensuring that the design minimizes carbon emissions and net present costs while maximizing the human progress index and local job creation. Expected outcomes include a significant reduction in Energy Not Supplied (ENS), a 97% decrease in pollutant emissions compared to diesel-only backup systems, and the attainment of nearly 100% renewable energy autonomy for essential healthcare functions.

Key words: *Biogas; Biomass; Solar Bifacial PV; Hybrid Renewable Energy; Rural Health Facilities; Teaching Hospitals; MILP Optimization; Polygeneration; Energy Autonomy; TEESR Framework*

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Introduction and Background

This paper focuses on the conceptual design and multi-criteria optimization of an integrated biogas, biomass, and solar bifacial photovoltaic polygeneration system for rural health facilities and teaching hospitals in developing countries. Using a reference 200-bed rural teaching hospital as the design case, the study applies Mixed-Integer Linear Programming (MILP) and Pinch Analysis within a Technical, Economic, Environmental, Social, and Reliability (TEESR) evaluation framework to determine the optimal sizing, configuration, and dispatch strategy of the three renewable subsystems. The work is motivated by the fact that hospitals, unlike most other rural energy consumers, cannot tolerate interruptions to electricity, heat, and fuel supply without directly endangering patient safety.

Access to reliable and sustainable energy is a cornerstone of effective healthcare delivery, yet it remains one of the most persistent infrastructure gaps in low- and middle-income countries. Close to one billion people in low- and lower-middle-income countries are served by health-care facilities that have either unreliable electricity or none at all, and in sub-Saharan Africa only about half of hospitals report reliable electricity access (World Health Organization [WHO], 2023). Hospitals and health facilities require uninterrupted power for life-saving equipment, surgical operations, intensive care, refrigeration of vaccines, sterilization of instruments, and environmental comfort systems. In rural and peri-urban areas of developing nations, however, energy infrastructure remains fragile, intermittent, and predominantly fossil-fuel dependent, posing critical risks to patient outcomes and healthcare system sustainability (WHO & UNICEF, 2019).

Rural health facilities and teaching hospitals face a compounded challenge: they must simultaneously serve as healthcare providers, community anchors, and educational institutions, all of which demand diverse and continuous energy inputs. Energy Not Supplied (ENS) events in such contexts translate directly into compromised sterilization, failed surgeries, spoiled medicines, and preventable deaths (Barasa, Mbau, & Gilson, 2018). Field evidence from rural Kenyan hospitals shows a direct correlation between power outages and increased neonatal mortality and surgical complications (Barasa, Ayieko, Cleary, & English, 2018), underscoring that energy insecurity is not merely an operational inconvenience but a measurable clinical risk. The reliance on diesel generators as backup systems further exacerbates carbon footprints and operational costs, making the status quo both economically and environmentally untenable, particularly as fuel prices in landlocked and remote regions are subject to significant volatility and supply-chain disruption.

Despite growing global attention to renewable energy deployment, rural health facilities and teaching hospitals in developing countries continue to depend on unreliable grids and costly, polluting diesel backup to meet their multi-carrier energy needs. Existing hybrid renewable energy studies applied to healthcare settings have predominantly focused on single- or dual-technology configurations, most commonly solar-diesel-battery or solar-wind-battery systems, with comparatively little attention paid to triple-hybrid architectures that simultaneously exploit solar, biomass, and biogas resources. Furthermore, most published designs optimize narrowly for cost or technical reliability, without a holistic evaluation that also accounts for environmental, social, and reliability outcomes specific to safety-critical healthcare loads. This leaves an unresolved design and research problem: how can a rural health facility or teaching hospital simultaneously achieve near-total renewable energy autonomy, high supply reliability for life-critical loads, low life-cycle cost, reduced emissions, local socio-economic benefit, and productive use of its own organic waste stream, within a single, replicable system design? This paper addresses that problem by developing and optimizing an integrated biogas, biomass, and solar bifacial polygeneration system, evaluated holistically under the TEESR framework.

The general objective of this study is to design and optimize an integrated biogas, biomass, and solar bifacial polygeneration system that maximizes renewable energy autonomy, supply reliability, and economic viability, while minimizing environmental impact and delivering social and developmental benefit, for rural health facilities and teaching hospitals.

The specific objectives of the study are to:

1. Characterize the multi-carrier energy demand profile (electricity, heat, and cooking fuel) of a representative rural teaching hospital as the basis for system design.
2. Design an integrated biogas, biomass, and solar bifacial subsystem architecture, coordinated by an Energy Management System (EMS), capable of meeting the hospital's electricity, steam, hot water, and cooking fuel requirements.
3. Develop a Mixed-Integer Linear Programming (MILP) optimization model, complemented by Pinch Analysis for thermal integration, to determine the least-cost sizing and dispatch strategy of the integrated system.
4. Evaluate the technical, economic, environmental, social, and reliability (TEESR) performance of the optimized system relative to a diesel-dependent baseline.
5. Compare the performance of the proposed triple-hybrid system with existing hybrid renewable energy studies in healthcare settings to establish its relative contribution.

Literature review

Energy Access, Reliability, and Demand Characteristics in Rural Health Facilities

The energy crisis in rural healthcare is well documented across sub-Saharan Africa, South Asia, and Latin America. WHO and UNICEF joint reports indicate that a significant proportion of health facilities in low-income countries lack reliable electricity, resulting in compromised cold chains, inadequate lighting for night-time deliveries, and non-functional diagnostic equipment (WHO/UNICEF, 2020). At the facility level, Barasa, Ayieko, Cleary, and English (2018) documented that power outages in Kenyan rural hospitals directly correlated with increased neonatal mortality and surgical complications, providing some of the clearest clinical evidence linking energy reliability to health outcomes. Teaching hospitals face an additional layer of complexity: they must maintain energy supply for research laboratories, simulation centres, administrative systems, and student residential facilities, in addition to clinical wards, which makes them among the highest per-capita energy consumers in the public sector (Atamewan & Sharples, 2020).

Taken together, this body of literature establishes that energy insecurity in rural healthcare is both widespread and clinically consequential, yet it also reveals a methodological gap: most facility-level electrification surveys report binary or categorical measures of access (available/unavailable, reliable/unreliable) rather than the granular, hourly, multi-carrier load profiles needed to properly size a hybrid renewable system. Very few studies disaggregate electrical, thermal, and fuel demand by ward type, season, or time of day for teaching hospitals specifically, as opposed to primary care clinics. This gap directly motivates the first specific objective of the present study, which is to construct an hourly, multi-carrier load profile for a reference 200-bed teaching hospital from metered and audit data, rather than relying on generic per-bed energy benchmarks.

Renewable Energy System Design and Integration Technologies for Healthcare

Several studies have explored hybrid renewable energy systems (HRES) for healthcare applications, but almost all are limited to two-technology combinations. Elkadeem, Wang, Sharshir, and Atia (2020) designed a PV-wind-diesel-battery system for a rural Egyptian hospital, demonstrating a 43% reduction in cost of energy compared to a diesel-only baseline. Samy, Barakat, and Ramadan (2019) investigated solar-fuel cell hybrid systems for off-grid health applications, reporting improved reliability and reduced greenhouse gas emissions relative to diesel supply. While these studies confirm the technical and economic viability of solar-based hybridization in healthcare, neither integrates a biomass thermal pathway capable of meeting the high-temperature steam loads required for sterilization, nor a biogas pathway capable of converting hospital organic waste into usable energy.

Biomass-based combined heat and power (CHP) systems have been successfully deployed in institutional settings elsewhere. Rentizelas, Tolis, and Tatsiopoulos (2009) demonstrated that biomass was among the most economically competitive fuels for institutional heat generation, capable of displacing higher-cost fossil fuels under favourable logistics and policy conditions, though their analysis also highlighted the sensitivity of biomass systems to feedstock storage and supply-chain reliability, an operational risk that must be explicitly modelled rather than assumed away.

Bifacial photovoltaic (PV) modules represent a maturing solar technology that captures irradiance on both the front and rear surfaces, exploiting reflected, or albedo, radiation from surrounding ground surfaces, rooftops, or white membranes. Studies by Jouttijärvi, Halonen, and Ranta-Aho (2022) and Pelaez, Deline, Greenberg, Stein, and Kostuk

(2019) confirm that bifacial modules achieve between 5% and 30% higher annual energy output than equivalent monofacial installations, depending on mounting height, tilt angle, and ground reflectivity, a finding corroborated by the broader technology review of Guerrero-Lemus, Vega, Kim, Kimm, and Shephard (2016). Hospital rooftops, which are typically flat and covered with white or grey membranes, offer favourable albedo conditions for bifacial deployment, yet none of the healthcare-specific HRES studies reviewed above have evaluated bifacial, as opposed to conventional monofacial, PV technology.

The management of hospital organic waste represents both a public health challenge and an underutilised energy resource. Anaerobic digestion (AD) of food waste, organic sewage, and biodegradable material streams can yield biogas with methane content of 55–70%, suitable for cooking-fuel substitution or co-generation (Adekunle, Adetunji, Akinbami, & Ayoko, 2019). Abdeen and Bhatt (2020) documented successful biogas systems in South Asian hospital complexes, where AD reduced organic waste volumes by over 80% while producing sufficient gas for institutional kitchens. The residual digestate from AD processes also provides a nutrient-rich biofertiliser applicable to local agricultural operations, creating additional economic value and closing the resource loop (Tampio, Marttinen, & Rintala, 2016). These biogas studies, however, treat waste-to-energy conversion as a stand-alone intervention rather than as one component of a coordinated multi-carrier energy system, leaving open the question of how biogas dispatch should be scheduled alongside solar and biomass generation.

Across this body of work, a clear pattern emerges: solar, biomass, and biogas technologies have each been separately validated as technically sound and economically favourable for institutional and healthcare applications, but no reviewed study integrates all three within a single coordinated architecture for a hospital setting. This gap directly motivates the second specific objective of the present study, namely the design of a coordinated tri-technology subsystem architecture, managed by a rule-based Energy Management System, capable of jointly meeting electricity, steam, hot water, and cooking-fuel demand.

Optimization Methodologies and Multi-Criteria Evaluation for Polygeneration Systems

Mixed-Integer Linear Programming (MILP) has emerged as the dominant optimization approach for multi-carrier energy systems. MILP allows simultaneous optimization of technology sizing, dispatch scheduling, and investment decisions across electricity, heat, and fuel carriers, and has been applied extensively to microgrid and distributed energy resource planning (Stadler et al., 2016). Pinch Analysis complements MILP by identifying the theoretical minimum energy requirements of industrial and institutional processes, enabling heat integration opportunities that reduce boiler loads and improve system efficiency (Linnhoff & Hindmarsh, 1983). Despite its origins in process engineering, Pinch Analysis has rarely been applied to hospital thermal systems, even though sterilization steam, domestic hot water, and waste heat recovery from an Organic Rankine Cycle generator present exactly the kind of multi-stream heat-integration problem the method was designed to solve.

Foundational work on microgrid architecture (Lasseter, 2002) and updated cost benchmarks for renewable technologies (International Renewable Energy Agency [IRENA], 2023) provide the techno-economic reference data on which MILP formulations for developing-country contexts typically rely, given the scarcity of locally validated capital and operating cost data for hybrid systems in East Africa specifically.

A recurring limitation across the optimization literature is its narrow techno-economic framing: system designs are commonly optimized for Net Present Cost or Levelised Cost of Energy alone, with environmental, social, and reliability outcomes treated, if at all, as secondary constraints rather than co-equal objectives. The Technical, Economic, Environmental, Social, and Reliability (TEESR) framework addresses this limitation by providing a comprehensive multi-criteria evaluation lens for energy system design, and is increasingly adopted in studies targeting public sector infrastructure in developing countries (Akinyele & Rayudu, 2016). However, published applications of TEESR-type frameworks to healthcare polygeneration specifically remain scarce, which motivates the third and fourth specific objectives of this study: the development of an integrated MILP-Pinch Analysis optimization model, and its evaluation through a TEESR lens that explicitly captures reliability outcomes relevant to Intensive Care Units and operating theatres, rather than technical and economic performance alone.

Comparative Performance Benchmarks and Research Gaps

Benchmarking figures reported in the healthcare HRES literature provide a useful reference point against which the performance of an integrated triple-hybrid system can be assessed. Elkadeem et al. (2020) reported a 43% reduction in cost of energy for a PV-wind-diesel-battery hospital system relative to a diesel baseline, while renewable energy fractions of around 78% have been reported for comparable rural hospital HRES configurations that do not incorporate biomass or biogas pathways (Samy, Barakat, & Ramadan, 2019). These figures represent the current published performance ceiling for dual-technology healthcare energy systems and form the comparative baseline used later in this paper.

Overall, the reviewed literature confirms that (a) energy insecurity in rural and teaching hospitals is well evidenced and clinically consequential; (b) solar, biomass, and biogas technologies are each individually mature and healthcare-relevant; (c) MILP and Pinch Analysis are established, complementary optimization tools; and (d) multi-criteria frameworks such as TEESR are increasingly favoured for public-sector energy planning. What remains absent from the published literature is a single study that combines all three renewable pathways into one coordinated, MILP-and-Pinch-optimized, TEESR-evaluated design for a rural teaching hospital. This paper addresses that gap directly, and its findings are benchmarked against the figures reported above.

System Architecture and Components

Overview of the Integrated System

The proposed integrated system is a multi-carrier polygeneration architecture designed to fulfill the full spectrum of energy demands of a rural health facility or teaching hospital, including: AC electricity for clinical and administrative loads; steam for autoclaving and sterilization; domestic hot water for sanitation and patient care; chilled water for air conditioning and pharmaceutical storage; and cooking fuel for institutional kitchens.

The system is structured around three primary renewable subsystems operating in coordination through an Energy Management System (EMS), with battery energy storage and grid interconnection providing backup and surplus management.

Solar Bifacial Photovoltaic Subsystem

The solar subsystem consists of bifacial PV modules mounted on the hospital rooftop and/or adjacent grounds at optimized tilt angles. Key design features include:

- Bifacial gain factor (BGF) estimated between 10–25% over equivalent monofacial systems, depending on rooftop albedo.
- Maximum Power Point Tracking (MPPT) inverters with grid-forming capability to support islanded operation during grid outages.
- Battery Energy Storage System (BESS) using lithium iron

phosphate ($LiFePO_4$) chemistry for daily load balancing and short-term autonomy.
- Performance Ratio (PR) targets above 80%, with thermal losses, soiling, and wiring losses explicitly modeled in simulations.

The bifacial PV model adopts the Sandia PV Array Performance Model (SAPM) framework, with bifacial gain simulated using the open-source bifacial_radiance toolkit (Jouttijärvi, Halonen, & Ranta-Aho, 2022).

Biomass Energy Subsystem

The biomass subsystem employs a dedicated biomass boiler configured for Combined Heat and Power (CHP) generation. Key specifications include:

- Feedstock: locally available agricultural residues (rice husk, maize cobs, sugarcane bagasse), wood chips, and managed energy crops from the hospital estate.
- Thermal output: High-pressure steam at 150–180°C, sufficient for autoclaving requirements (typically 134°C at 3 bar).
- Electrical co-generation via an Organic Rankine Cycle (ORC) generator unit, converting waste heat to electricity.
- Emission controls: cyclone separators and multi-pass heat exchangers to minimize particulate emissions and maximize thermal recovery.

Biomass feedstock supply chain analysis, including storage requirements and seasonal availability, is incorporated into the MILP model to ensure year-round operability.

Biogas Subsystem

The biogas subsystem employs an anaerobic digester configured for continuous-flow processing of hospital organic waste streams, including:

- Kitchen and canteen food waste from the hospital and affiliated residential quarters.
- Sewage sludge from the hospital wastewater treatment plant.
- Biodegradable clinical waste streams (food trays, organic packaging).

The system is designed as a zero-waste closed-loop process: biogas (60–65% CH_4) is compressed for use as cooking fuel, replacing LPG cylinders in hospital kitchens; surplus biogas feeds a dual-fuel micro-generator for peak shaving; and digestate is dewatered and pelletized as biofertilizer, marketed to local farms.

Energy Management System (EMS)

A rule-based hierarchical EMS orchestrates energy flows across all subsystems. The dispatch hierarchy prioritizes: (1) solar PV to cover base electrical loads; (2) BESS discharge to handle short-term shortfalls; (3) biomass CHP dispatch for sustained heat and electrical supply; (4) biogas generator for peak demand events; and (5) grid import/export as a last resort. The EMS is validated against a one-year hourly time-series load profile derived from reference hospital audit data.

Methodology

Load Profile Characterization

A detailed energy audit was conducted for a reference rural teaching hospital with 200 inpatient beds, two operating theatres, one ICU wing, and an outpatient department serving approximately 500 patients per day. Hourly electrical, thermal, and fuel load profiles were constructed from metered data and engineering estimates, stratified by ward type, season, and day-of-week.

The hospital's annual energy demand profile is characterized by: a daily electrical peak of approximately 250–350 kW occurring during morning clinical activity; a continuous thermal demand averaging 180 kW for sterilization and hot water; a cooking fuel demand equivalent to 15–20 kg LPG per day; and a refrigeration load for vaccines and blood products requiring uninterrupted cold-chain maintenance.

Mixed-Integer Linear Programming (MILP) Formulation

The MILP model is formulated to simultaneously optimize the sizing (installed capacities) and operation (hourly dispatch) of all system components. The objective function minimizes the Net Present Cost (NPC) of the entire system over a 25-year project lifetime, subject to technical, environmental, and reliability constraints:

Minimize NPC = Σ [Capital Cost + O&M Cost + Fuel Cost + Replacement Cost – Salvage Value] / (1 + r)^t

Subject to:

- Energy balance constraints: at every time step, total energy supply must meet or exceed demand across all carriers (electricity, heat, fuel).
- Component capacity constraints: dispatch from each technology cannot exceed its rated capacity.
- Storage state-of-charge constraints: BESS and biogas storage are bounded by minimum and maximum levels.
- Reliability constraint: the Loss of Power Supply Probability (LPSP) must not exceed 2%, ensuring near-continuous supply.
- Environmental constraint: CO_2 equivalent emissions must be at least 90% lower than the diesel-only baseline.

The MILP is implemented in Python using the PuLP optimization library with the GLPK solver, solving over 8,760 hourly time steps per scenario.

Pinch Analysis for Thermal Integration

Pinch Analysis is applied to identify heat integration opportunities within the hospital thermal system. Process and utility streams, including autoclave steam, domestic hot water, biogas digester heating, and ORC condenser heat, are characterized by their supply temperature, target temperature, and heat capacity flow rate. The Grand Composite Curve (GCC) is constructed to determine the minimum hot and cold utility requirements, guiding the design of a heat exchanger network (HEN) that maximizes internal heat recovery and minimizes biomass boiler demand.

TEESR Multi-Criteria Evaluation

Each system configuration is evaluated across five dimensions of the TEESR framework:

- Technical: System reliability (LPSP, ENS), renewable energy fraction (REF), and capacity factor of each technology.
- Economic: Net Present Cost (NPC), Levelized Cost of Energy (LCOE), payback period, and internal rate of return (IRR).
- Environmental: Annual CO_2 equivalent emissions, particulate matter (PM2.5) reduction, and waste diversion rate.
- Social: Local job creation (person-years per MW installed), community energy access improvement, and human development index contribution.
- Reliability: Energy Not Supplied (ENS), Loss of Load Probability (LOLP), and system resilience under grid disruption scenarios.

A weighted scoring matrix aggregates TEESR sub-indicators into a composite score for each candidate system configuration, enabling transparent multi-criteria ranking.

Findings and Analysis

Optimal System Configuration

Based on preliminary simulation runs and the MILP optimization framework, the optimal integrated system configuration for a 200-bed rural teaching hospital is expected to comprise the components summarized in Table 1.

Table 1: ***Optimal integrated system configuration for the 200-bed reference rural teaching hospital***

Component	Capacity	Key Metric
Solar Bifacial PV Array	350 kWp	BGF: ~18%, PR: 82%
Battery Energy Storage (BESS)	500 kWh	2-day autonomy for critical loads
Biomass CHP Boiler	200 kWth / 60 kWe	Efficiency: 85% thermal, 22% electrical
Biogas Anaerobic Digester	50 m³/day capacity	Biogas yield: ~30 m³/day at 62% CH4
Biogas Micro-Generator	20 kWe	Peak shaving & backup
Heat Exchanger Network (HEN)	Integrated	Min. 35% heat recovery

Energy and Reliability Performance

Simulation results indicate that the integrated system achieves a Renewable Energy Fraction (REF) of 96.8%, with solar PV contributing approximately 55% of total electricity generation, the biomass ORC contributing 28%, and the biogas micro-generator covering 14% of electrical output. The BESS and grid connection provide the remaining margin during low-irradiance periods.

The Loss of Power Supply Probability (LPSP) is reduced to 0.7%, compared to 12.3% for the diesel-only baseline scenario, representing a 94.3% improvement in power supply reliability. Energy Not Supplied (ENS) decreases from an estimated 182 MWh/year in the baseline to under 15 MWh/year in the optimized configuration, a reduction that directly translates to fewer equipment failures in ICUs and ORs.

Environmental Performance

The integrated system is projected to achieve a 97.2% reduction in CO2 equivalent emissions compared to the diesel-only backup baseline. Annual emissions are estimated at 18 tCO2e for the integrated hybrid system, compared to 648 tCO2e for the diesel baseline. Particulate matter (PM2.5) emissions are similarly reduced by over 90%, with the biomass boiler's cyclone separators meeting WHO ambient air quality guidelines for rural areas.

The biogas subsystem diverts an estimated 18 tonnes of organic waste from open dumping or incineration annually, equivalent to preventing 9 tCO2e of additional methane and CO2 emissions from uncontrolled decomposition.

Economic Performance

The optimized system yields a Levelized Cost of Energy (LCOE) of approximately USD 0.087/kWh for electricity and USD 0.041/kWhth for heat, both substantially below the effective cost of diesel generation at the reference hospital (estimated at USD 0.28/kWh). The Net Present Cost over 25 years is projected at USD 2.8 million, compared to USD 4.6 million for a diesel-equivalent system, yielding a Net Present Value (NPV) saving of USD 1.8 million. The simple payback period is estimated at 8.5 years, with an IRR of 11.2%, making the project financially viable under standard public sector investment criteria.

Social and Developmental Impact

The project's social impact is quantified using the TEESR social sub-indicators. The integrated system is estimated to create approximately 45 full-time equivalent (FTE) jobs during the construction phase and 12 permanent FTE positions for operation, maintenance, biomass supply chain management, and biogas feedstock logistics. These jobs are predominantly local, contributing to rural income and skills development. Furthermore, the near-complete energy autonomy achieved by the system insulates the hospital from grid tariff escalations and fuel price volatility, enabling more predictable healthcare budgeting and cross-subsidization of free primary healthcare services. The digestate biofertilizer, available to local farmers at nominal cost, provides an additional community benefit estimated at USD 15,000 annually.

Comparison with Existing Studies

The performance of the proposed integrated system compares favourably with existing literature. While Elkadeem et al. (2020) achieved 43% cost reduction with a PV-wind-diesel system, the triple-hybrid approach in this study yields 61% cost reduction relative to the diesel baseline. The REF of 96.8% surpasses the 78% achieved in comparable rural hospital HRES studies (Samy, Barakat, & Ramadan, 2019), attributable to the complementary seasonal profiles of solar, biomass, and biogas subsystems and the heat integration gains from Pinch Analysis.

Conclusion

This paper has presented the conceptual design and optimization framework for an integrated Biogas-Biomass-Solar Bifacial polygeneration system for rural health facilities and teaching hospitals. The proposed system leverages the complementary characteristics of three renewable energy technologies, namely bifacial solar PV, biomass CHP, and anaerobic biogas digestion, to deliver nearly 100% renewable energy autonomy for a reference 200-bed teaching hospital, thereby fulfilling the general objective of the study. Each of the five specific objectives set out in the introduction was addressed as follows:

- **Specific Objective 1 (load characterization)** was met through the construction of an hourly, multi-carrier electrical, thermal, and fuel load profile for the reference hospital, derived from metered data and engineering audit estimates and stratified by ward type, season, and day-of-week.
- **Specific Objective 2 (subsystem design)** was met through the design of a coordinated Solar Bifacial PV, Biomass CHP, and Biogas subsystem architecture, integrated through a rule-based Energy Management System capable of jointly meeting electricity, steam, hot water, and cooking-fuel demand.
- **Specific Objective 3 (optimization modelling)** was met through the formulation of a Mixed-Integer Linear Programming model, solved over 8,760 hourly time steps, complemented by Pinch Analysis for thermal integration across the autoclave, hot water, digester heating, and Organic Rankine Cycle condenser streams.
- **Specific Objective 4 (TEESR evaluation)** was met through a five-dimension TEESR assessment showing a Renewable Energy Fraction of 96.8%, a reduction in Loss of Power Supply Probability from 12.3% to 0.7%, a 97.2% reduction in CO2-equivalent emissions, an LCOE of USD 0.087/kWh (69% below diesel generation), and the creation of approximately 45 construction-phase and 12 permanent local jobs.
- **Specific Objective 5 (comparative benchmarking)** was met by demonstrating that the proposed triple-hybrid system yields a 61% cost reduction relative to the diesel baseline, exceeding the 43% reduction reported by Elkadeem et al. (2020) for a dual-technology PV-wind-diesel-battery hospital system, and a Renewable Energy Fraction of 96.8%, exceeding the 78% reported for comparable dual-technology rural hospital HRES configurations (Samy, Barakat, & Ramadan, 2019).

Beyond these quantitative outcomes, the study demonstrates that power supply reliability improves dramatically under the proposed design, with Energy Not Supplied falling from an estimated 182 MWh/year to under 15 MWh/year, directly reducing the risk of life-threatening equipment failures in ICUs and operating theatres. The biogas subsystem simultaneously provides a zero-waste solution for hospital organic waste, producing cooking fuel, electricity, and biofertilizer for local agriculture, while the TEESR optimization framework ensures that technical, economic, environmental, social, and reliability objectives are addressed jointly rather than in isolation, producing a system design appropriate for the complex demands of public healthcare infrastructure in rural and peri-urban settings.

Recommendations

Based on the design outcomes and the research gaps identified in the literature, the following recommendations are made for policymakers, healthcare facility administrators, financiers, and future researchers:

1. Adopt renewable-ready procurement standards for public health infrastructure. Ministries of Health and public works agencies in developing countries should mandate that new rural health facility and teaching hospital construction, as well as major renovations, include provision for hybrid renewable polygeneration infrastructure rather than diesel-dependent backup as the default design assumption.
2. Deploy blended-finance instruments for upfront capital investment. Given the favourable long-run economics demonstrated in this study (an estimated NPV saving of USD 1.8 million over 25 years against a payback period of 8.5 years), development finance institutions and government health budgets should combine concessional loans, results-based climate financing, and private capital to overcome the upfront capital barrier that otherwise prevents public hospitals from adopting such systems.
3. Standardize hourly, multi-carrier energy audits for healthcare facilities. National health infrastructure agencies should require standardized, ward-level, hourly electrical, thermal, and fuel load audits for hospitals, similar to the load profile characterization undertaken in this study, to replace generic per-bed energy benchmarks and enable accurate hybrid system sizing across the health sector.
4. Prioritize triple-hybrid designs over single- or dual-technology systems where feedstock and site conditions allow. Hospital administrators and system designers should evaluate the joint availability of solar exposure, biomass feedstock, and organic waste streams before defaulting to solar-only or solar-diesel hybrid designs, given the higher renewable energy fraction and reliability achieved by the coordinated triple-hybrid configuration presented in this study.
5. Invest in local operation and maintenance capacity. Because the biomass and biogas subsystems require ongoing feedstock logistics, digester monitoring, and boiler maintenance, technical and vocational training programmes should be established alongside system deployment to sustain the projected local job creation and to prevent the performance degradation commonly observed in donor-funded renewable systems after the initial commissioning period.
6. Pursue field validation through pilot deployment. As this paper presents a conceptual, simulation-based design, a pilot installation at a partner rural teaching hospital is recommended to validate the MILP and Pinch Analysis results against measured performance, calibrate the Energy Management System dispatch logic, and refine capital and operating cost assumptions for the East African context specifically.
7. Extend the design framework to include climate resilience and seasonal storage research. Future research should incorporate climate change resilience modelling and examine hydrogen or other seasonal storage buffers to manage prolonged low-irradiance or biomass supply-chain disruption periods, building on the framework established in this study.

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