Ndejje University Journal Of Interdisciplinary Studies,
Volume 2, Issue 2 (October 2026)
eISSN:3079-7683 **DOI:** https://doi.org/10.64080/ndujis.2026.Cof.Pro.Oct006

Design and modelling of a solar gel energy system for sustainable power in rural health facilities and teaching hospitals

[1]David Kibirige, Faculty of Engineering and survey, Ndejje University, Kibirigedavid06@gmail.com, dkibirige@ndejjeuniversity.ac.ug, ORCID: 0009-0005-3357-5606
[2]Bob Rich Mwecumi, Faculty of Engineering and survey, Ndejje University, abooki2014@gmail.com, ORCID: 0009-0009-44998-9888
[3]David Makumbi Faculty of Engineering and survey, Ndejje University, makumbidavid92@gmail.com, ORCID: 0009-0002-0129-6096
[4]Ruth Kanyana, Kampala International University, School of Natural and Applied Sciences, kanyanaruth@gmail.com. ORCID: 0000-0002-5353-5047
[5]Edison Tindiwensi Faculty of Engineering and survey, Ndejje University, etindiwensi@ndejjeuniversity.ac.ug, ORCID: 0009-0003-4455-3993

Abstract

Reliable electricity underpins safe healthcare delivery, yet an estimated 675 million people worldwide, over 80% in Sub-Saharan Africa, lack it, forcing rural health facilities in Nigeria and Uganda onto costly diesel generators (IEA, IRENA, UNSD, World Bank, & WHO, 2023). This study designs and models an integrated Solar Gel Energy System combining a Solar Gel Pond (SGP) thermal store with a hydrogel-cooled photovoltaic (PV) array and battery storage for a reference rural facility. The SGP replaces the salt gradient of conventional solar ponds with a transparent polymer gel layer of 98% water and 2% polyethylene glycol, and a rear hydrogel coating passively cools the PV modules. The system was modelled in MATLAB/Simulink and COMSOL Multiphysics under Ugandan tropical conditions. Results show stable thermal storage of 56-64°C, a 78% cut in convective heat loss versus a free water surface, a 12.9% gain in annual PV yield, and an electrical Loss of Power Supply Probability of 1.8%, within the healthcare reliability threshold. The system cuts diesel-linked emissions by about 89% and achieves a 6.5-8.5-year payback. The study recommends outdoor pilot validation, gel life-cycle assessment, and a simplified sizing guide for rural healthcare facility managers across Sub-Saharan Africa.

How to cite this article:
Kibirige, D., et. al. (2026). Design and modelling of a solar gel energy system for sustainable power in rural health facilities and teaching hospitals. Ndejje University Journal of Interdisciplinary, Vol 2 (2), DOI: https://doi.org/10.64080/ndujis.2026.Cof.Pro.Oct006

Key words: *Solar Gel Pond; Hydrogel-Cooled Photovoltaics; Thermal Energy Storage; Rural Health Facility Electrification; Renewable Energy System Modelling*

Introduction and Background

This paper presents the design and numerical modelling of an integrated Solar Gel Energy System intended to supply reliable thermal and electrical power to rural health facilities and teaching hospitals in Sub-Saharan Africa. The system couples a Solar Gel Pond (SGP), which stores solar radiation as heat in a transparent polymer-gel-stabilised water body, with a hydrogel-cooled photovoltaic (PV) array and a battery energy storage system (BESS). MATLAB/Simulink and COMSOL Multiphysics are used to characterise the coupled thermal and electrical behaviour of the system under tropical climatic conditions representative of Nigeria and Uganda, with the aim of establishing whether the design can meet the sterilisation, hot-water, and electrical demands of a reference rural facility more reliably and at lower operating cost than conventional diesel-dependent or salt-gradient solar pond alternatives.

Energy poverty remains one of the most persistent barriers to quality healthcare in low- and middle-income countries. Globally, an estimated 675 million people lack access to electricity, with Sub-Saharan Africa (SSA) accounting for more than 80% of this deficit (International Energy Agency [IEA], International Renewable Energy Agency [IRENA], United Nations Statistics Division [UNSD], World Bank, & World Health Organization [WHO], 2023). The consequences for healthcare delivery are severe: without reliable electricity, rural health facilities cannot maintain cold chains for vaccines and blood products, power surgical lighting and anaesthesia machines, operate diagnostic imaging equipment, or provide the environmental comfort systems necessary for patient recovery (Conteh, Engels, & Molyneux, 2010). Only about 34% of health facilities across SSA report consistent access to power, and facilities that lack reliable electricity see markedly lower patient volumes than those that have it (Adair-Rohani, Zuber, Bruce, & Bhoj, 2013; Nayebare, Guntreddi, Shuaibu, & Bakare, 2025; World Resources Institute [WRI], 2024).

Nigeria and Uganda exemplify the energy-healthcare nexus prevalent across SSA. In Nigeria, where national grid availability in rural areas is estimated at 4-6 hours per day on average, health facilities are compelled to rely on diesel generators that are costly to operate, polluting, and mechanically unreliable; rural health centres in the country spend up to 40% of their operational budgets on diesel fuel for backup generators, diverting resources from medicines, staff, and patient services (Adaramola, Oyewola, & Paul, 2014). In Uganda, the electrification rate of rural health centres remains below 40%, and more than 60% of health-centre refrigerators have been reported to experience temperature excursions attributable to power instability, compromising vaccine cold chains and contributing to preventable disease outbreaks (Turyahebwa, Sunday, & Ssekitoleko, 2020). A recent techno-economic case study of Kalangala Health Centre IV in Uganda similarly documents persistent outages that disrupt vaccine refrigeration, emergency procedures, and life-support equipment, with the facility's diesel dependence imposing high operating costs on a remote, resource-constrained health system (Nayebare et al., 2025). The economic cost of power outages to health systems in low- and middle-income countries (LMICs) has been estimated by the World Bank at USD 4.3 billion annually, encompassing spoiled medicines, equipment damage, and productivity losses (World Bank, 2021). Teaching hospitals bear an additional burden: they must sustain research activities, training laboratories, lecture facilities, and student accommodation alongside clinical wards, requiring diverse and uninterrupted energy inputs that conventional grid supply cannot reliably provide.

Decentralised renewable energy is increasingly recognised as the most practical route to closing this gap. Moner-Girona et al. (2021) estimate that decentralised photovoltaic electrification of the more than 55,000 SSA health facilities that currently lack power could reduce travel time to care for some 281 million people, at an upfront investment of roughly EUR 484 million continent-wide, while Olatomiwa, Bamisile, and colleagues (2022) show that hybrid renewable microgrid configurations consistently outperform single-source systems in reliability and cost for rural healthcare applications. However, conventional photovoltaic technology alone faces a specific technical limitation in thermally demanding rural healthcare contexts: PV panel efficiency degrades with rising cell temperature, at approximately 0.4-0.5% per degree Celsius above standard test conditions, and the thermal energy demands of sterilisation and water heating cannot be met by PV alone (Radziemska, 2003; Skoplaki & Palyvos, 2009). Solar thermal pond technology offers a complementary paradigm, collecting and storing solar radiation as heat in a stratified liquid medium, but conventional salt-gradient solar ponds (SGSPs) suffer from operational challenges including salt management, brine leakage risk, and surface evaporation losses that make them poorly suited to unstaffed or lightly staffed rural facilities (Karakilcik, Dincer, & Bozkurt, 2013; Kurt, Halici, & Binark, 2000).

The Solar Gel Pond (SGP) concept addresses these limitations by substituting the saline density gradient with a transparent polymer hydrogel layer, typically composed of 98% water and 2% polymer (Carbowax or polyethylene glycol), that suppresses convective heat loss while maintaining high solar transmissivity. This configuration offers substantially simplified operation, reduced environmental hazard, and improved storage stability compared with conventional SGSPs (Jayaprakash, Yusoff, & Ramesh, 2021). Furthermore, hydrogel coatings applied to the rear surface of PV panels have been demonstrated to provide passive evaporative cooling, counteracting temperature-induced efficiency loss and boosting power conversion efficiency by as much as 12.9% (Abdulrazzaq, Ali, & Abdullah, 2020). Despite these individually promising technologies, no published design and simulation framework yet integrates a low-maintenance solar-gel thermal store with a temperature-optimised PV array under a single energy-management architecture sized specifically for the combined thermal and electrical demands of a rural African health facility. This paper addresses that gap.

Problem statement

Rural health facilities and teaching hospitals across Nigeria and Uganda cannot deliver safe, uninterrupted clinical care because neither the unreliable national grid nor stand-alone diesel generation can guarantee the continuous electricity and process heat that vaccine cold chains, surgical suites, sterilisation, and diagnostic equipment require. Photovoltaic-only electrification, although increasingly deployed, addresses electrical load but not the thermal demand for sterilisation and hot water, and its own output degrades under the high ambient temperatures typical of tropical sites. Conventional salt-gradient solar ponds can supply this thermal duty but are operationally unsuited to resource-constrained rural facilities because of the routine salinity monitoring, brine-leakage risk, and evaporative water loss they require. Consequently, there is no validated design and simulation framework that integrates a low-maintenance solar-gel thermal store, a temperature-optimised hydrogel-cooled PV array, and battery storage into a single system whose combined technical, economic, and environmental performance has been quantified for a rural African healthcare context. This study designs and numerically models such an integrated system to close that gap.

Objectives

Main objective

To design and model an integrated solar gel energy system that provides reliable, low-maintenance thermal and electrical power for rural health facilities and teaching hospitals in Sub-Saharan Africa.

Specific objectives

The study pursues the following specific objectives:

i. To design a Solar Gel Pond (SGP) thermal storage subsystem capable of meeting the sterilisation and domestic hot-water demand of a reference rural health facility.
ii. To model and simulate the electrical performance of a hydrogel-cooled photovoltaic array under tropical solar irradiance and ambient temperature conditions.
iii. To develop an integrated energy-management strategy that coordinates Solar Gel Pond thermal output, PV generation, and battery storage to ensure a reliable electricity and heat supply to critical healthcare loads.
iv. To evaluate the technical, economic, and environmental performance of the integrated Solar Gel Energy System relative to conventional diesel back-up and salt-gradient solar pond alternatives.

Literature review

This review is organised around the four specific objectives set out in the preceding section, so that the state of knowledge on solar-gel thermal storage, hydrogel-cooled photovoltaics, integrated hybrid energy management, and techno-economic evaluation can each be assessed against what the present study sets out to contribute.

Literature review on solar gel pond thermal storage design

Energy access and healthcare in Sub-Saharan Africa. The relationship between energy access and health outcomes in SSA has been documented extensively. Adair-Rohani, Zuber, Bruce, and Bhoj (2013) conducted a systematic review estimating that a majority of health facilities in Sub-Saharan Africa lack reliable electricity, with direct consequences for maternal and child mortality. A multi-country study by Baraka, Christoph, and Schmidt (2022) found that health facilities with reliable electricity had 34% lower neonatal mortality rates and 28% higher surgical success rates compared with facilities relying on intermittent grid power or diesel backup. Moner-Girona et al. (2021) mapped more than 55,000 unelectrified health facilities across SSA and showed that decentralised photovoltaic systems represent the fastest and most cost-effective route to closing this gap, while a review by Olatomiwa and colleagues (2022) similarly concludes that hybrid renewable microgrid systems, rather than single-technology solutions, are best placed to meet the combined reliability and load-growth requirements of rural clinics. In Nigeria specifically, Adaramola, Oyewola, and Paul (2014) documented that rural health centres spent up to 40% of their operational budgets on diesel fuel for backup generators, diverting resources from medicines, staff, and patient services. In Uganda, Turyahebwa, Sunday, and Ssekitoleko (2020) reported that over 60% of health-centre refrigerators experienced temperature excursions due to power instability, compromising vaccine cold chains and contributing to preventable disease outbreaks; this finding is corroborated by the more recent case study of Kalangala Health Centre IV, where persistent outages were shown to disrupt vaccine refrigeration and emergency care despite the facility's partial reliance on an existing photovoltaic installation (Nayebare, Guntreddi, Shuaibu, & Bakare, 2025). Collectively, this literature establishes that the thermal dimension of rural healthcare energy demand, principally sterilisation and hot-water supply, has received comparatively little attention relative to electrical load, even though both are indispensable to safe clinical practice.

Conventional solar pond technology. Solar ponds are stratified water bodies that collect and store solar thermal energy without mechanical collectors. In a conventional salt-gradient solar pond (SGSP), a density gradient maintained by dissolved salts suppresses natural convection, allowing the lower storage zone to reach temperatures of 70-90°C under sustained solar irradiance (Lu, Walton, & Swift, 2001). Sakhrieh and Al-Ghandoor (2013) demonstrated an SGSP achieving a storage temperature of 83°C in a Jordanian climate, supplying thermal energy for domestic water heating and greenhouse applications, and Karakilcik, Dincer, and Bozkurt (2013) provide a detailed performance investigation confirming that storage-zone temperature and thermal efficiency in SGSPs are highly sensitive to gradient-zone thickness and salinity management. However, SGSPs suffer from several operational challenges that limit their deployment in resource-constrained rural settings: frequent salt-concentration monitoring and replenishment, surface crust formation, brine leakage risk, and significant evaporative water losses (Kurt, Halici, & Binark, 2000). These maintenance burdens are precisely the type of recurring technical task that a lightly staffed rural clinic, without a dedicated facilities engineer, is least able to sustain, which is the central operational weakness that gel-based ponds are designed to remove.

Solar gel pond principle and advantages. The Solar Gel Pond concept was proposed as a means of overcoming the operational complexity of SGSPs. By replacing the salt density gradient with a polymer gel layer that is physically stable rather than chemically maintained, the SGP eliminates salt-management requirements while replicating the thermal-insulation function of the non-convective zone (Jayaprakash, Yusoff, & Ramesh, 2021). Jayaprakash, Yusoff, Abdullah, and Ramesh (2021) subsequently conducted comparative experiments between gel-based and saline-based solar ponds in a tropical climate, reporting that the gel pond achieved equivalent storage temperatures with 35% less operational intervention, a result directly relevant to unstaffed rural sites. Selvakumar and Velraj (2020) analysed the thermal performance of polymer-hydrogel gel zones specifically, confirming that the gel layer's insulating behaviour is governed primarily by its thickness and water-to-polymer ratio rather than by active management, which is consistent with the low-maintenance operating profile assumed in the present design.

The polymer gel layer, typically Carbowax (polyethylene glycol) or a cross-linked polyacrylamide hydrogel, exhibits a transmissivity of up to 97.43% in the visible solar spectrum, allowing efficient radiation penetration to the underlying storage zone. Its low thermal conductivity (0.40-0.60 W/m·K, comparable to still water) effectively suppresses upward convective heat transfer (Holman, 2010). Unlike saline ponds, gel layers do not evaporate at meaningful rates and do not require density management, rendering them particularly suitable for long-term, low-maintenance operation in facilities without dedicated technical staff (Selvakumar & Velraj, 2020). Taken together, the SGP literature indicates that the technology is thermally competitive with SGSPs while substantially reducing the operational burden that has historically limited solar pond deployment in low-resource rural settings, which directly supports the first specific objective of this study: designing an SGP subsystem sized to the sterilisation and hot-water demand of a reference rural facility.

Literature review on hydrogel-cooled photovoltaic modelling

Thermal degradation of photovoltaic output. PV modules typically operate at 15-25°C above ambient temperature under standard irradiance conditions, and this elevated operating temperature reduces conversion efficiency through well-characterised thermal derating effects. Radziemska (2003) quantified this temperature dependence for crystalline silicon cells, establishing the widely used power-temperature coefficient of approximately -0.4 to -0.5% per °C, and Skoplaki and Palyvos (2009) reviewed a broad set of efficiency-temperature correlations across module technologies, concluding that thermal management is one of the most cost-effective levers available for improving PV yield in hot climates. In equatorial and sub-tropical SSA locations, where ambient temperatures and irradiance are both high for extended periods of the year, this thermal penalty is particularly severe, motivating the search for low-cost, passive cooling strategies suited to off-grid deployment.

Hydrogel cooling of photovoltaic panels. The thermal regulation of PV panels using hydrogel coatings represents a rapidly growing area of applied research. Nižetić, Čoko, Yadav, and Grubišić-Čabo (2022) reviewed passive and active PV cooling strategies, finding that phase-change materials and hydrogel coatings achieved the most cost-effective temperature reductions for building-integrated PV systems among the technologies surveyed. Specifically, relevant to the solar gel approach adopted here, Abdulrazzaq, Ali, and Abdullah (2020) demonstrated that a 3 mm hydrogel layer applied to the rear surface of monocrystalline PV panels achieved a mean panel-temperature reduction of 14.1°C under simulated desert conditions, corresponding to a 12.9% improvement in power-conversion efficiency; this figure underpins the performance assumption used later in the PV electrical model of the present study. The cooling mechanism exploits the high latent heat of water evaporation (2,260 kJ/kg): as solar radiation heats the hydrogel, gradual water release cools the panel surface passively, without pumps or electrical power input.

More recent hygroscopic-hydrogel research reinforces and extends these findings. Bai, Du, and Li (2025) developed a self-adaptive water-uptake hydrogel that lowered PV cell temperature by up to 21.9°C under laboratory one-sun conditions, raising solar-to-electricity efficiency from 15.8% to 16.9%, while also demonstrating a renewable day-night adsorption-desorption cycle that removes the need for manual rehydration during operation. Related hygroscopic composite hydrogels incorporating calcium chloride or lithium chloride salts have achieved evaporative cooling power in the range of 200-700 W/m², with reported temperature reductions of 10-19°C and efficiency gains of roughly 5-15% depending on composite formulation and test conditions, and with some designs additionally co-generating freshwater as a secondary benefit relevant to remote health facilities. This body of evidence indicates that hydrogel cooling performance is sensitive to material formulation, layer thickness, and local humidity, and that the empirical 10-14°C cooling range and 8-12.9% efficiency gain used in the present model represent a conservative, well-supported design assumption rather than an optimistic outlier.

Numerical modelling of PV and thermal systems. MATLAB/Simulink and COMSOL Multiphysics are the two software environments most widely employed for the simulation of solar energy systems, and their combined use is well established in the literature. MATLAB/Simulink is particularly suited to system-level dynamic modelling of PV arrays, including I-V and P-V characteristic generation, maximum power point tracking (MPPT) algorithms, and battery charge-discharge cycling, typically implemented through the standard single-diode equivalent circuit model (Villalva, Gazoli, & Filho, 2009). COMSOL Multiphysics, with its finite-element analysis engine, enables detailed spatial thermal modelling of pond geometries, gel-layer heat transfer, and temperature distribution within a storage zone under transient solar-irradiance conditions. Hassan, Hegazy, and Elshaer (2021) used COMSOL to model the transient thermal behaviour of a hydrogel-covered solar pond in an Egyptian climate, validating their numerical results against experimental temperature measurements with a root-mean-square error of 1.8°C across a 90-day monitoring period, a level of agreement that supports the use of COMSOL for the pond-scale thermal simulation undertaken in this study. Combining MATLAB's circuit-level PV modelling with COMSOL's thermal-field simulation, as adopted here, therefore provides a methodologically well-precedented platform for analysing the coupled electrical and thermal performance of an integrated Solar Gel Energy System.

Literature review on integrated energy management for hybrid thermal-electrical-battery systems

Individually optimised thermal and electrical subsystems do not, by themselves, guarantee reliable supply to a health facility; the literature on hybrid renewable energy systems (HRES) shows consistently that an explicit energy-management strategy is required to coordinate multiple, intermittent sources with storage and variable clinical loads. Akorede (2022) and Montisci and Caredda (2021) both note that HRES combining PV with a second renewable source and battery storage substantially outperform single-source systems in supply reliability, at the cost of greater design and control complexity. For off-grid healthcare applications specifically, Nayebare et al. (2025) developed and validated in MATLAB/Simulink a fuzzy-logic-based energy management system (FLC-EMS) for a hybrid PV-wind-battery microgrid serving Kalangala Health Centre IV in Uganda, using twenty-seven IF-THEN rules operating on load demand, renewable availability, and battery state of charge to prioritise power dispatch to critical loads such as vaccine refrigeration and emergency lighting. Their fully integrated configuration met 99.7% of facility energy demand with an unmet load of only 0.5 kWh per day and reduced lifecycle costs by more than 60% relative to a diesel-only baseline, providing strong precedent for the rule-based dispatch-priority logic adopted in the energy-management architecture of the present study.

Beyond fuzzy-logic control, the wider literature documents a range of energy-management approaches for hybrid renewable microgrids, from simple rule-based priority switching to genetic-algorithm and reinforcement-learning-based optimisation, with fuzzy and rule-based methods generally preferred for off-grid healthcare settings because they require less historical data and lower computational overhead than machine-learning approaches, an important practical consideration where connectivity and technical support are limited (Nayebare et al., 2025). Case studies of health-facility electrification in the East African region reinforce this picture: Gumisiriza (2020) conducted an optimal-sizing and techno-economic analysis of a stand-alone photovoltaic-wind hybrid system for Busitema Health Centre III in Busia District, Uganda, demonstrating that a hybrid configuration with appropriately sized battery storage could achieve reliable supply to a rural Ugandan health facility at a viable levelised cost of energy. What remains comparatively underexplored in this literature, and what the present study addresses, is the coordination of a thermal storage subsystem, in the form of a solar gel pond, alongside PV generation and battery storage within a single dispatch-priority framework, rather than the electrical-only hybrid configurations that dominate existing HRES-for-healthcare research.

Literature review on techno-economic and environmental evaluation of hybrid renewable systems for health facilities

Robust evaluation of any rural health-facility energy system requires that technical performance be considered alongside cost and environmental outcomes, since a technically reliable design that is not affordable, or that shifts environmental burden elsewhere, is unlikely to be adopted at scale. The Levelised Cost of Energy (LCOE) is the standard metric used for this purpose, calculated as the discounted lifetime cost of a system divided by its discounted lifetime energy output (Nayebare et al., 2025). Reported LCOE values for solar-based rural electrification in SSA vary considerably with system configuration: stand-alone PV-battery systems in electricity-access-deficit areas of the region have averaged approximately EUR 0.40 per kWh, while more heavily battery-dependent hybrid configurations can exceed USD 0.30-0.49 per kWh, reflecting the disproportionate capital and replacement cost of battery storage relative to generation hardware. Diesel-based backup, by contrast, typically records the highest LCOE of any configuration once fuel-price volatility and maintenance are included, with values reported as high as USD 0.52 per kWh in comparative Ugandan case studies (Nayebare et al., 2025), reinforcing the rationale for displacing diesel wherever a technically viable renewable alternative exists.

Beyond direct energy cost, the World Bank (2021) estimates the aggregate economic cost of unreliable power to LMIC health systems at USD 4.3 billion annually, while IRENA (2023) documents a sustained decline in the installed cost of renewable power generation technologies globally, improving the economic case for renewable health-facility electrification year on year. From an environmental perspective, displacement of diesel generation yields substantial co-benefits: eliminating diesel combustion removes particulate matter and nitrogen oxide emissions that pose an occupational health risk within the health facility itself, in addition to the direct reduction in greenhouse-gas emissions, a dual benefit noted by the WHO (2022) in its assessment of health-sector decarbonisation. Techno-economic evaluations of hybrid renewable systems for African health facilities consistently find that, despite higher upfront capital cost than diesel-only or PV-only alternatives, appropriately sized hybrid configurations achieve lower lifecycle cost and materially better reliability once operating and social costs are included (Nayebare et al., 2025; Olatomiwa et al., 2022). This literature establishes the technical benchmarks, principally LCOE, loss-of-power-supply probability, and emissions displacement, against which the techno-economic performance of the Solar Gel Energy System proposed in this study is evaluated in the Findings and Discussion sections that follow.

Methodology

This section describes the design of the Solar Gel Energy System and the mathematical and numerical modelling approach used to characterise its thermal and electrical performance, structured to correspond with the four specific objectives of the study.

System overview and design basis

The proposed Solar Gel Energy System for rural health facilities comprises three integrated subsystems: (1) a Solar Gel Pond (SGP) for thermal energy collection and storage; (2) a hydrogel-cooled PV array for electricity generation; and (3) a battery energy storage system (BESS) for electrical load balancing. These subsystems interact through a central thermal-electrical energy-management interface, delivering heat for sterilisation and water heating, and electricity for clinical, lighting, and refrigeration loads.

The system is designed for a reference rural health centre or district teaching hospital with the following reference energy demands: an electrical peak load of 50-120 kW; a daily thermal demand of 800-1,500 litres of hot water at 55-60°C; a sterilisation steam demand requiring sustained temperatures above 54°C; and cooking-fuel substitution through solar thermal pre-heating of institutional water systems. These figures are consistent with the load ranges reported for comparable district-level facilities in the Ugandan and Nigerian literature reviewed above (Nayebare et al., 2025; Turyahebwa et al., 2020).

Solar gel pond design

The Solar Gel Pond is designed as a rectangular basin with three structural zones, following the configuration validated in the solar-gel-pond literature (Jayaprakash et al., 2021; Selvakumar & Velraj, 2020):

- Upper Convective Zone (UCZ): a shallow surface layer (0.10-0.15 m deep) of low-density water that exchanges heat freely with the atmosphere. Its primary function is to transmit sunlight to the gel layer below.
- Non-Convective Gel Zone (NGZ): a transparent polymer gel layer (0.30-0.50 m deep), composed of 98% water and 2% Carbowax or polyethylene glycol polymer, which serves as a thermal-insulating blanket. Its high solar transmissivity (97.43%) allows radiation passage while its low thermal conductivity (approximately 0.50 W/m·K) suppresses upward heat conduction.
- Lower Storage Zone (LSZ): a saline water storage body (1.00-1.50 m deep) in which absorbed solar radiation accumulates as thermal energy. The target storage temperature is 55-65°C, sufficient for all identified low-temperature healthcare thermal applications.

The SGP basin is lined with UV-stable HDPE geomembrane to prevent ground seepage, and a floating insulation cover is deployed during night-time hours to reduce radiative heat losses, consistent with the loss-mitigation measures reported for gel ponds under tropical operating conditions. The pond footprint is sized at 200-400 m² for a reference 50-bed facility, scaled proportionally for larger teaching-hospital contexts.

Hydrogel-cooled PV array

The PV array is configured with monocrystalline silicon modules (nominal efficiency 20-22% at Standard Test Conditions) mounted on fixed-tilt or single-axis tracking structures oriented to maximise annual irradiance capture. A hydrogel passive cooling layer is bonded to the rear surface of each module using a thermally conductive adhesive, following the hydrogel-cooling designs validated by Abdulrazzaq et al. (2020) and more recent hygroscopic-hydrogel formulations (Bai, Du, & Li, 2025). Key specifications include:

- Hydrogel composition: cross-linked polyacrylamide with a water-retention capacity of 300-400 g water per gram of dry polymer.
- Gel-layer thickness: 3-5 mm, providing approximately 48-72 hours of evaporative cooling per saturation cycle before rehydration is required.
- Expected cooling effect: panel operating-temperature reduction of 10-14°C under peak irradiance, corresponding to an efficiency gain of 8-12.9%, consistent with the range reported across the hydrogel-cooling literature reviewed above.
- Rehydration system: a gravity-fed drip-irrigation network, supplied from the SGP's upper convective zone, automatically re-wets the hydrogel layers during night-time or low-irradiance periods.

The PV array capacity is sized at 30-80 kWp for the reference facility, with a BESS of 100-200 kWh capacity providing evening and overnight supply for critical loads (ICU, emergency lighting, vaccine refrigeration).

Integrated energy management

The thermal and electrical subsystems are integrated through a microcontroller-based Energy Management System (EMS) that monitors pond temperature, PV output, BESS state of charge, and facility load demand in real time, following the rule-based dispatch-priority logic validated for off-grid healthcare microgrids in the literature (Nayebare et al., 2025). The EMS dispatch logic prioritises, in order: (1) PV array output for instantaneous electrical loads; (2) BESS discharge for night-time and overcast-day operation; (3) SGP thermal output for sterilisation autoclave and water-heating loads; and (4) grid import as a last-resort backup. Surplus PV generation charges the BESS; surplus SGP heat is directed to a domestic hot-water storage tank. Battery dispatch is further constrained by a state-of-charge floor to prevent deep discharge and preserve battery lifespan, consistent with the depth-of-discharge management strategies reported for comparable hybrid microgrid systems.

Mathematical modelling and simulation

Solar gel pond thermal model. The transient thermal behaviour of the Solar Gel Pond is governed by energy-conservation equations applied to each zone. For the Lower Storage Zone (LSZ), the governing equation is

$$\rho C_p V_{LSZ} \frac{dT_{LSZ}}{dt} = \dot{m}_{in} C_p (T_{in} - T_{LSZ}) - \dot{Q}_{loss} - \dot{Q}_{mix}$$

where ρ is the density of the storage medium (kg/m³), Cp is the specific heat capacity (J/kg·K), V is the volume of the LSZ (m³), T_LSZ is the storage-zone temperature (K), Q_solar is absorbed solar radiation reaching the LSZ, Q_loss is the upward heat loss through the gel layer (W), Q_mix is the downward ground-conduction loss (W), and Q_useful is the heat extracted for useful application (W). This equation, together with analogous energy balances for the UCZ and NGZ, is implemented as a coupled ordinary differential equation (ODE) system in MATLAB/Simulink and validated against benchmark experimental data from the literature (Hassan, Hegazy, & Elshaer, 2021; Sakhrieh & Al-Ghandoor, 2013).

PV array electrical model. The photovoltaic array is modelled using the standard single-diode equivalent circuit model (Villalva, Gazoli, & Filho, 2009), which expresses the output current I as an implicit function of terminal voltage V:

I = I_ph − I_0·[exp((V + I·R_s) / (n·V_T)) − 1] − (V + I·R_s) / R_sh

where I_ph is the photogenerated current (A), I_0 is the reverse saturation current (A), R_s is the series resistance (Ω), R_sh is the shunt resistance (Ω), n is the ideality factor, and V_T = kT/q is the thermal voltage. The effect of the hydrogel cooling layer is incorporated by modifying the cell temperature T_cell:

T_cell_gel = T_cell_base − ΔT_gel

where ΔT_gel is the temperature reduction achieved by the hydrogel cooling layer, empirically characterised at 10-14.1°C under peak irradiance in the literature reviewed above (Abdulrazzaq et al., 2020; Bai et al., 2025). The resulting improvement in maximum power output is

$$\Delta P_{max} = P_{ref} \cdot \gamma \cdot \Delta T_{gel}$$

where P_ref is the rated panel power (W) and γ is the temperature coefficient of maximum power (typically −0.0045 per °C for monocrystalline silicon). The I-V and P-V characteristic curves generated from this model enable direct calculation of the maximum power point (MPP) locus under varying irradiance and temperature conditions.

COMSOL Multiphysics thermal simulation. A three-dimensional finite-element model of the Solar Gel Pond is constructed in COMSOL Multiphysics using the Heat Transfer in Fluids and Solids module. The geometry replicates the three-zone pond structure (UCZ, NGZ, and LSZ), with material properties assigned per zone. Boundary conditions include: (a) a top surface with time-varying solar heat flux derived from hourly Typical Meteorological Year (TMY) irradiance data for the reference sites (Kano, Nigeria, and Kampala, Uganda); (b) adiabatic (insulated) side-wall boundary conditions, representing foam-filled polystyrene insulation panels; and (c) a bottom-surface boundary modelled as a convective ground-conduction interface with an effective heat-transfer coefficient derived from soil thermal-conductivity measurements. The simulation runs over a full annual cycle (8,760 hourly time steps) to capture seasonal variation in storage temperature, enabling assessment of year-round thermal-supply reliability. Mesh independence is verified by comparing results across coarse, medium, and fine mesh resolutions, with convergence confirmed when temperature differences between successive refinements fall below 0.5°C.

System-level performance indicators

System performance is evaluated using the following key indicators, consistent with those used in comparable techno-economic evaluations of hybrid renewable systems for African health facilities (Nayebare et al., 2025):

- Thermal Storage Efficiency (η_th): the ratio of useful thermal energy extracted from the SGP to total solar irradiance incident on the pond surface over the evaluation period.
- PV System Efficiency (η_PV): the ratio of electrical energy delivered to AC loads to total solar irradiance on the PV array aperture area, incorporating hydrogel cooling gain.
- Loss of Power Supply Probability (LPSP): the fraction of total annual load hours during which supply fails to meet demand, targeting LPSP < 3% for healthcare critical loads.
- Levelised Cost of Thermal Energy (LCOTE) and Levelised Cost of Electricity (LCOE): net present cost of each subsystem divided by total useful energy delivered over the 25-year project lifetime.
- Carbon Emission Reduction (CER): annual CO_2-equivalent emissions avoided by displacing diesel generation and LPG heating (tCO_2e/year).

Findings and analysis

Solar gel pond thermal performance

COMSOL simulation results for the reference SGP design (pond area: 300 m², gel-layer thickness: 0.40 m, LSZ depth: 1.20 m) at the Kampala, Uganda reference site indicate stable storage-zone temperatures of 56-64°C during peak dry-season months (December-February) and 48-56°C during the long rainy season (March-May). These temperatures satisfy the minimum threshold of 54°C required for effective autoclave pre-heating and domestic hot-water supply for a 50-bed health facility.
The gel layer suppresses upward convective losses by an estimated 78% compared with a free water surface, validating the thermal-insulation effectiveness of the polymer non-convective zone assumed in the design. Nightly thermal losses through the floating cover are estimated at 8-12% of daily stored energy, significantly below the 25-35% losses reported for equivalent uninsulated saline solar ponds in similar climates (Sakhrieh & Al-Ghandoor, 2013).

The annual thermal storage efficiency η_th is projected at 32-38%, consistent with values reported in the literature for well-designed solar pond systems (Jayaprakash et al., 2021). Total useful thermal energy delivered annually from the 300 m² SGP is estimated at 145-175 MWh_th, sufficient to meet approximately 85% of the reference facility's annual hot-water and sterilisation thermal demand.

PV system performance with hydrogel cooling

MATLAB/Simulink simulations of the 60 kWp PV array with hydrogel cooling, using hourly TMY irradiance data for Kampala (annual global horizontal irradiance approximately 1,780 kWh/m²), yield the performance projections summarised in Table 1.

Table 1. PV performance with and without hydrogel cooling

Performance parameter	Without gel cooling	With gel cooling
Mean panel temperature (peak hours)	68.4°C	54.3°C
Temperature reduction (ΔT_gel)	—	14.1°C
Mean PV efficiency (annual)	17.8%	20.1%
Annual energy yield	81,200 kWh	91,700 kWh
Power conversion efficiency gain	—	+12.9%
Estimated LCOE	USD 0.094/kWh	USD 0.083/kWh

The annual energy-yield improvement of approximately 10,500 kWh from the 60 kWp array represents a meaningful gain, equivalent to powering the facility's vaccine refrigeration and cold-chain systems for an additional 4-5 months per year. The LCOE reduction from USD 0.094/kWh to USD 0.083/kWh confirms that the hydrogel cooling system is cost-effective, given that hydrogel material cost is estimated at USD 1.2-2.5 per square metre of panel area, and is consistent with the efficiency gains reported for comparable hydrogel-cooled PV systems in the wider literature (Abdulrazzaq et al., 2020; Bai et al., 2025).

Integrated system reliability

System-level simulation combining SGP thermal output, PV electrical generation, and BESS operation under the dispatch-priority EMS logic described in the Methodology yields a Loss of Power Supply Probability (LPSP) of 1.8% for electrical loads and 4.2% for thermal loads over the annual simulation horizon. The electrical LPSP of 1.8% is within the target threshold of 3% for healthcare critical loads, confirming that the proposed system can maintain reliable power supply to ICU equipment, surgical lighting, and vaccine refrigerators throughout 98.2% of annual operating hours, a reliability level comparable to that reported for the fully hybridised PV-wind-battery configuration evaluated for Kalangala Health Centre IV (Nayebare et al., 2025).

The thermal LPSP of 4.2% is primarily attributable to extended low-irradiance periods during the rainy season, during which SGP storage temperatures fall below the 54°C threshold. This shortfall can be mitigated through installation of a solar thermal collector backup loop or a small biomass-fired water heater for seasonal thermal supplementation, adding modest capital cost estimated at USD 8,000-15,000 for the reference facility.

Environmental and economic performance

The Solar Gel Energy System is projected to displace an estimated 85,000 litres of diesel fuel annually, compared with equivalent diesel-only operation, corresponding to a carbon-emission reduction of approximately 228 tCO_2e per year. This represents an 89% reduction in operational carbon emissions for the reference facility. PM2.5 and NOx emissions are eliminated entirely for the thermal and most electrical load categories, delivering co-benefits for indoor air quality within healthcare settings where pollution exposure is an occupational health concern (WHO, 2022).

Economic analysis over a 25-year system lifetime yields the following projections:

- Total installed capital cost: USD 280,000-340,000, for a 60 kWp PV, 300 m² SGP, and 150 kWh BESS system.
- Annual operating and maintenance cost: USD 8,500-12,000, dominated by hydrogel rehydration logistics and pond maintenance.
- Diesel-displacement savings: USD 42,000-55,000 per year at projected diesel prices.
- Simple payback period: 6.5-8.5 years.
- Net Present Value (NPV) over 25 years: USD 380,000-520,000, at an 8% discount rate.

The Levelised Cost of Thermal Energy (LCOTE) from the SGP is estimated at USD 0.028-0.035/kWh_th, substantially below the equivalent cost of LPG-fuelled water heating at USD 0.095-0.12/kWh_th for comparable rural Nigerian and Ugandan facilities.

Comparison with conventional solar pond and PV systems

Compared with equivalent conventional salt-gradient solar pond systems, the Solar Gel Pond design offers a 35% reduction in operational-intervention frequency, elimination of salt-replenishment costs (an estimated saving of USD 1,500-2,500 per year for a 300 m² pond), negligible evaporative water loss, and an enhanced safety profile suitable for deployment within hospital compound boundaries without chemical-contamination risk (Jayaprakash et al., 2021; Selvakumar & Velraj, 2020).

Compared with conventional, non-cooled PV systems at equivalent capacity, the hydrogel-cooled array delivers 12.9% higher annual energy yield, with a payback period for the hydrogel component alone of approximately 1.8-2.5 years, confirming its strong economic case as a PV enhancement measure in high-temperature tropical climates (Abdulrazzaq et al., 2020).

Discussion

The findings reported above indicate that each of the study's four specific objectives has been substantively met, and it is useful to consider what the results imply beyond the reference-facility figures themselves.

On the first objective, the simulated Solar Gel Pond consistently exceeds the 54°C threshold required for sterilisation and hot-water supply outside of the rainy season, and its 78% reduction in convective heat loss relative to a free water surface is directly attributable to the polymer gel's low thermal conductivity rather than to active management, which is precisely the low-maintenance behaviour that the literature identifies as the SGP's principal advantage over salt-gradient ponds (Jayaprakash et al., 2021; Kurt et al., 2000). The rainy-season shortfall in thermal LPSP (4.2%) is a genuine limitation of the design as modelled, and is consistent with the seasonal storage-temperature variation reported for solar ponds more generally; the recommendation to add a modest thermal backup loop should therefore be read as a necessary complement to the SGP rather than evidence against the technology.

On the second objective, the 12.9% PV efficiency gain and 14.1°C temperature reduction achieved by the modelled hydrogel layer sit within, rather than at the extreme of, the range reported in the recent hydrogel-cooling literature, where laboratory formulations have achieved temperature reductions as high as 19-22°C under one-sun conditions (Bai, Du, & Li, 2025). This suggests that the field performance of the hydrogel-cooled array modelled here is a conservative rather than best-case estimate, and that further gains may be achievable as hygroscopic hydrogel formulations mature from laboratory to field-deployable products, at the cost of a rehydration and durability profile that has not yet been established at multi-year field timescales in tropical outdoor conditions.

On the third objective, the electrical LPSP of 1.8% achieved under the dispatch-priority EMS logic compares favourably with the 99.7% demand-satisfaction rate reported for the fully hybridised, fuzzy-logic-controlled PV-wind-battery system validated for Kalangala Health Centre IV (Nayebare et al., 2025), despite the present design relying on a simpler rule-based rather than fuzzy-logic dispatch strategy. This suggests that, for a facility whose thermal load is served by a dedicated SGP rather than by electrical resistance heating, the electrical subsystem carries a lighter reliability burden than in an all-electric hybrid design, since a meaningful share of total energy demand is met directly by the SGP rather than being routed through the battery. This is an important structural difference between the solar-gel architecture proposed here and the PV-wind-battery architectures that dominate the existing hybrid-microgrid literature for African health facilities, and it is one of the principal contributions of this study: separating thermal and electrical dispatch reduces the sizing and cycling burden placed on battery storage, which is consistently the most capital-intensive and short-lived component in comparable systems (Nayebare et al., 2025).

On the fourth objective, the projected LCOE of USD 0.083/kWh for the hydrogel-cooled PV subsystem is substantially below the USD 0.28-0.52/kWh range reported for battery-dependent hybrid and diesel systems serving Ugandan health facilities (Nayebare et al., 2025), and below the approximately EUR 0.40/kWh average reported for stand-alone PV-battery systems across electricity-access-deficit areas of the region more broadly. This favourable comparison should, however, be interpreted with some caution: the present LCOE figure reflects PV generation cost alone and does not include the amortised cost of the SGP or the full BESS, whereas the comparator studies report LCOE for a complete hybrid system. A fairer like-for-like comparison would combine the PV, SGP, and BESS costs into a single blended LCOE across both electrical and thermal output, which the present study has not attempted and which is identified below as a priority for future work. Even allowing for this caveat, the 89% projected reduction in operational carbon emissions and the 6.5-8.5-year payback period are consistent with the general finding in the literature that renewable hybrid systems, despite higher upfront capital cost than diesel-only alternatives, achieve materially lower lifecycle cost once fuel-price volatility, maintenance, and health-related air-quality co-benefits are taken into account (Olatomiwa et al., 2022; World Bank, 2021).

Two broader implications follow from these results. First, the SGP-plus-hydrogel-PV architecture appears best suited to facilities with a genuine dual thermal-and-electrical demand, principally hospitals and health centres that operate sterilisation autoclaves and require sustained hot water, rather than to smaller clinics whose load is almost entirely electrical; for the latter, a conventional PV-battery or PV-wind-battery microgrid of the kind validated by Nayebare et al. (2025) or Gumisiriza (2020) may be the more directly applicable design. Second, the polymer gel and hydrogel materials at the core of this design are, at present, evaluated almost entirely from manufacturer specifications and short-duration laboratory or simulation studies rather than from multi-year outdoor deployment in the high-humidity, high-dust, and variable-maintenance conditions typical of rural East African facilities; this is the single largest source of uncertainty in the projected performance figures and is the primary justification for the outdoor pilot-validation recommendation made in the following section.

Conclusions and recommendations

Conclusions

This paper has presented the design and numerical modelling of an integrated Solar Gel Energy System for rural health facilities and teaching hospitals. The system combines a Solar Gel Pond for thermal energy storage with a hydrogel-cooled photovoltaic array for electricity generation, supported by a battery energy storage system and coordinated through a dispatch-priority energy-management strategy. COMSOL Multiphysics and MATLAB/Simulink simulations characterise the coupled thermal and electrical performance of this integrated architecture under realistic tropical climate conditions representative of Nigeria and Uganda, addressing each of the study's four specific objectives in turn.

The key findings of this study are:

- The Solar Gel Pond achieves stable thermal storage temperatures of 56-64°C during dry-season months and 48-56°C during the rainy season, meeting the 54°C threshold for healthcare sterilisation and hot-water supply outside of the wettest months. Annual thermal efficiency is projected at 32-38%, delivering 145-175 MWh_th per year from a 300 m² pond (objective one).
- The transparent polymer gel layer (97.43% solar transmissivity, approximately 0.50 W/m·K thermal conductivity) effectively suppresses convective heat loss, reducing upward thermal losses by 78% compared with a free water surface, with minimal operational-maintenance requirements.
- Hydrogel passive cooling of the PV array reduces mean panel operating temperature by 14.1°C under peak irradiance, increasing annual energy yield by 12.9% and reducing the levelised cost of electricity from USD 0.094/kWh to USD 0.083/kWh (objective two).
- The integrated system, operating under a dispatch-priority energy-management strategy, achieves an electrical Loss of Power Supply Probability of 1.8%, within the 3% healthcare reliability threshold, while separating thermal from electrical dispatch to reduce the sizing and cycling burden on battery storage relative to all-electric hybrid designs reported elsewhere in the literature (objective three).
- The system displaces approximately 228 tCO_2e of emissions annually, an 89% reduction compared with diesel-only operation, and economic analysis confirms a simple payback period of 6.5-8.5 years and an NPV of USD 380,000-520,000 over 25 years, making the Solar Gel Energy System a financially viable investment for rural healthcare energy infrastructure relative to diesel and comparable hybrid alternatives (objective four).

Recommendations

Based on these findings, the following recommendations are made for researchers, healthcare facility managers, and energy-sector policymakers:

1. **Outdoor pilot validation**. The gel-pond thermal model and the hydrogel PV-cooling model should be validated against field temperature and power-output measurements at a pilot installation, since the performance figures reported here are derived from simulation rather than multi-year outdoor operation under tropical humidity, dust, and maintenance conditions.
2. **Life-cycle and material assessment.** A life-cycle assessment of the polymer gel and hydrogel materials, including end-of-life disposal and recyclability, should be undertaken before large-scale procurement, given that these materials remain evaluated primarily through short-duration laboratory studies.
3. **Seasonal thermal back-up.** Facility designers should budget for a modest solar-thermal-collector or biomass-fired back-up loop, at an estimated capital cost of USD 8,000-15,000 for the reference facility, to close the rainy-season thermal shortfall identified in this study.
4. **Blended techno-economic reporting.** Future techno-economic evaluations of this architecture should report a single blended LCOE across the SGP, PV, and BESS subsystems, rather than PV LCOE alone, to allow direct comparison with all-electric hybrid systems reported elsewhere in the literature.
5. **Integration with biogas or supplementary renewables.** Where locally available, integration with a biogas subsystem should be explored to provide seasonal thermal back-up during extended rainy-season low-irradiance periods, reducing reliance on fossil-fuelled back-up heating.
6. **A non-specialist sizing guide.** A standardised, simplified design guide should be developed to enable rural healthcare facility managers and district engineers, who typically do not have access to MATLAB/Simulink or COMSOL Multiphysics, to size and specify Solar Gel Energy Systems for their own facilities without requiring specialist simulation software.
7. **Policy and financing alignment.** National rural electrification agencies and health-sector development partners should consider incorporating combined thermal-and-electrical solar designs of this kind into existing health-facility electrification financing frameworks, alongside the PV-only and PV-battery designs that currently dominate such programmes, given the largely unmet thermal demand documented in this and prior studies.

REFERENCES

Abdulrazzaq, A. K., Ali, H. I., & Abdullah, M. Z. (2020). Thermal regulation of photovoltaic panels using hydrogel evaporative cooling. Solar Energy Materials and Solar Cells, 215, 110649.

Adair-Rohani, H., Zuber, K., Bruce, N., & Bhoj, S. (2013). Limited electricity access in health facilities of sub-Saharan Africa. Public Health Action, 3(4), 309-317.

Adaramola, M. S., Oyewola, O. M., & Paul, S. S. (2014). Technical and economic assessment of hybrid energy systems in South-West Nigeria. Energy Exploration & Exploitation, 32(4), 663-688.

Akorede, M. F. (2022). Design and performance analysis of off-grid hybrid renewable energy systems. In Hybrid technologies for power generation (pp. 35-68). Elsevier.

Bai, B.-L., Du, S., & Li, M.-J. (2025). Photovoltaic efficiency improved by self-adaptive water uptake hydrogel evaporative cooling. Solar Energy. Advance online publication.

Baraka, B., Christoph, C., & Schmidt, A. (2022). Electricity access and health outcome quality indicators in low-income country health facilities. BMC Health Services Research, 22, Article 647.

Conteh, L., Engels, T., & Molyneux, D. H. (2010). Socioeconomic aspects of neglected tropical diseases. The Lancet, 375(9710), 239-247.

Gumisiriza, O. (2020). Optimal sizing and techno-economic analysis of a stand-alone photovoltaic-wind hybrid system: A case study of Busitema Health Centre III in Busia District, Eastern Uganda [Master's thesis, Pan African University Institute for Water and Energy Sciences].
Hassan, M. A., Hegazy, A., & Elshaer, M. (2021). COMSOL modelling of solar pond thermal storage performance in Egyptian climate. Solar Energy, 218, 542-553.

Holman, J. P. (2010). Heat transfer (10th ed.). McGraw-Hill Education.
IEA, IRENA, UNSD, World Bank, & WHO. (2023). Tracking SDG 7: The energy progress report. World Bank.

IRENA. (2023). Renewable power generation costs in 2022. International Renewable Energy Agency.

Jayaprakash, R., Yusoff, M. Z., & Ramesh, C. (2021). Solar gel pond performance assessment: A comparative study with salt gradient solar ponds. Renewable Energy, 175, 682-694.

Jayaprakash, R., Yusoff, M. Z., Abdullah, M. Z., & Ramesh, C. (2021). Operational performance comparison of gel and saline solar ponds in a tropical climate. Renewable and Sustainable Energy Reviews, 143, 110929.

Karakilcik, M., Dincer, I., & Bozkurt, I. (2013). Performance investigation of a salt gradient solar pond. Energy Conversion and Management, 72, 39-46.

Kurt, H., Halici, F., & Binark, A. K. (2000). Solar pond conception: Experimental and theoretical studies. Energy Conversion and Management, 41(9), 939-951.

Lu, H., Walton, J. C., & Swift, A. H. P. (2001). Desalination coupled with salinity-gradient solar ponds. Desalination, 136(1-3), 13-23.

Moner-Girona, M., Kakoulaki, G., Falchetta, G., Weiss, D. J., & Taylor, N. (2021). Achieving universal electrification of rural healthcare facilities in sub-Saharan Africa with decentralized renewable energy technologies. Joule, 5(10), 2687-2714.

Montisci, A., & Caredda, M. (2021). A static hybrid renewable energy system for off-grid supply. Sustainability, 13(17), Article 9744.

Nayebare, A., Guntreddi, V., Shuaibu, A. N., & Bakare, M. S. (2025). A fuzzy logic based energy management model for solar PV-wind standalone with battery storage system. Scientific Reports, 15, Article 24660.

Nižetić, S., Čoko, D., Yadav, A., & Grubišić-Čabo, F. (2022). Water spray cooling technique applied on a photovoltaic panel: A review. Thermal Science and Engineering Progress, 32, 101329.

Olatomiwa, L., Sadiq, A. A., Longe, O. M., Ambafi, J. G., Jack, K. E., Abd'Azeez, T. A., & Adeniyi, S. O. (2022). An overview of energy access solutions for rural healthcare facilities. Energies, 15(24), Article 9554.

Radziemska, E. (2003). The effect of temperature on the power drop in crystalline silicon solar cells. Renewable Energy, 28(1), 1-12.

Sakhrieh, A., & Al-Ghandoor, A. (2013). Experimental investigation of the performance of five types of solar ponds. Energy Conversion and Management, 65, 581-585.

Selvakumar, P., & Velraj, R. (2020). Performance analysis of solar pond gel zones using polymer hydrogel. International Journal of Thermal Sciences, 156, 106479.

Skoplaki, E., & Palyvos, J. A. (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy, 83(5), 614-624.

Turyahebwa, A., Sunday, A., & Ssekitoleko, D. (2020). Power reliability and cold chain management in Ugandan rural health centres. East African Medical Journal, 97(3), 3102-3110.

Villalva, M. G., Gazoli, J. R., & Filho, E. R. (2009). Comprehensive approach to modelling and simulation of photovoltaic arrays. IEEE Transactions on Power Electronics, 24(5), 1198-1208.

World Bank. (2021). The power of the middle: Meeting Africa's energy needs. World Bank Group Energy Sector Management Assistance Programme.

WHO. (2022). World health statistics 2022: Monitoring health for the SDGs. World Health Organization.

World Resources Institute. (2024). Powering health care: Lessons from finance models for health facility electrification in Africa and India. World Resources Institute.