

Review

Solar Energy Solutions for Healthcare in Rural Areas of Developing Countries: Technologies, Challenges, and Opportunities

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Abstract

Recently, solar energy technologies are a cornerstone of the global effort to transition towards cleaner and more sustainable energy systems. However, in many rural areas of developing countries, unreliable electricity severely impacts healthcare delivery, resulting in reduced medical efficiency and increased risks to patient safety. This review explores the transformative potential of solar energy as a sustainable solution for powering healthcare facilities, reducing dependence on fossil fuels, and improving health outcomes. Consequently, energy harvesting is a vital renewable energy source that captures abundant solar and thermal energy, which can sustain medical centers by ensuring the continuous operation of life-saving equipment, lighting, vaccine refrigeration, sanitation, and waste management. Beyond healthcare, it reduces greenhouse gas emissions, lowers operational costs, and enhances community resilience. To address this issue, the paper reviews critical solar energy technologies, energy storage systems, challenges of energy access, and successful solar energy implementations in rural healthcare systems, providing strategic recommendations to overcome adoption challenges. To fulfill the aims of this study, a focused literature review was conducted, covering publications from 2005 to 2025 in the Scopus, ScienceDirect, MDPI, and Google Scholar databases. With targeted investments, policy support, and community engagement, solar energy can significantly improve healthcare access in underserved regions and contribute to sustainable development.

Keywords: renewable energy; solar energy; energy storage; rural healthcare; off-grid solutions; solar-powered health centers



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1. Introduction

Access to reliable energy is a fundamental pillar of modern healthcare. However, in many rural areas of developing countries, healthcare facilities suffer from energy poverty, leading to inconsistent services, deteriorating patient care, and preventable deaths. Essential medical functions such as vaccine refrigeration, surgical lighting, sterilization, clean water supply, sanitation, and waste management depend on electricity. Without reliable power, rural healthcare facilities struggle to provide even basic services, let alone handle emergencies or complex medical procedures. Given these challenges, addressing the energy gap in rural healthcare facilities is an urgent priority, especially as they confront infectious diseases, maternal health complications, and chronic illnesses in regions most vulnerable to climate change. Solar energy, a clean, renewable, and increasingly cost-effective resource,

offers a viable solution. It reduces dependency on fossil fuels while aligning with key Sustainable Development Goals (SDGs), including good health and well-being (SDG 3), clean energy access (SDG 7), and climate action (SDG 13).

In many developing countries, household energy needs have traditionally been met through biomass fuels such as firewood, along with fossil fuels, agricultural waste, diesel, and kerosene for cooking, boiling water, and lighting. This dependence contributes to air pollution, exacerbates global warming, and leads to environmental degradation, including deforestation and ozone layer depletion [1]. Moreover, the lack of reliable electricity has significantly reduced the quality and availability of primary healthcare in rural facilities, leading to fewer medical interventions and increased health risks, particularly for women and children. Beyond healthcare, ensuring reliable electricity in rural areas promotes broader socio-economic development.

Access to electricity can improve education, drive economic growth, promote environmental sustainability, and enhance the overall quality of life [2]. Providing clean water, effective sanitation, and sustainable environmental practices is essential for public health [3]. Furthermore, modern healthcare facilities require electricity for critical functions such as vaccine refrigeration, blood storage, sterilization, and diagnostic equipment. However, only about 34% of hospitals in sub-Saharan Africa currently have reliable electricity access. While recent data from two countries indicate gradual improvements, ambitious strategies are still required to enhance healthcare services in the region [4]. Transitioning toward a more sustainable future, renewable energy plays a crucial role in reducing greenhouse gas emissions, improving energy security, and promoting economic resilience. By reducing reliance on imported fossil fuels, renewable energy contributes to achieving key economic and political objectives [5]. Solar, wind, biomass, biogas, hydropower, and geothermal energy sources offer cleaner alternatives that support environmental sustainability and economic progress [6]. The feasibility and efficiency of these energy systems depend on factors such as location, availability of resources, and technology selection. With advancements in solar energy and declining costs, these solutions are becoming more affordable and accessible, offering a path toward a cleaner and more sustainable energy future.

According to the International Energy Agency (IEA), solar photovoltaic (PV) technology has become the cheapest source of electricity in many regions, making it an attractive option for healthcare facilities transitioning to renewable energy [7]. While other renewable sources like biomass, wind, and hydropower are viable, they often face geographical and logistical challenges and require higher installation costs. Thus, solar energy presents an optimal solution for sustainable healthcare electrification in rural areas.

This paper reviews the latest solar energy technologies that can transform rural healthcare systems in developing countries. It explores how solar energy can power critical healthcare infrastructure, analyzes the economic feasibility of adopting these technologies, and presents case studies of successful solar projects that have improved healthcare delivery. The paper also discusses challenges to solar energy adoption and proposes strategies to overcome these barriers through policy reforms, community involvement, and investments in energy storage systems. By examining the intersection of energy and healthcare, this review highlights the transformative potential of solar energy in achieving sustainable healthcare solutions in underserved regions.

Methodology

In this review, a systematic search of the literature was conducted using the Scopus, ScienceDirect, MDPI, and Google Scholar databases, covering publications from 2005 to 2025, and resulting in a comprehensive collection of references representing the most relevant studies on solar energy solutions in isolated rural areas of developing countries.

To ensure quality, peer-reviewed publications were considered, following the recommendations in [8]. In addition, uniform search criteria were applied across all databases to maintain methodological consistency, and articles with titles unrelated to the area of interest were excluded. Duplicates were manually removed, and reference management tools such as Mendeley were used to track records throughout the process; however, limitations of this review include the restriction to English-language publications.

The search keywords included: “Renewable energy in developing countries,” “Solar energy for rural healthcare,” “Off-grid solar energy,” “Rural health centers,” “Sustainable energy solutions,” and “Health benefits. And abstracts were screened to confirm the relevance to the topic, with a focus on solar energy technologies applied to rural healthcare in developing countries, and full-text articles meeting the inclusion criteria were retrieved and analyzed in detail to extract data on technology types, implementation challenges, benefits, and policy recommendations.

2. Solar Energy Technologies

Solar energy, a widely utilized form of renewable energy, can be harnessed either directly from sunlight or indirectly through various methods. Solar panels can be installed on rooftops, vehicles, bodies of water, and parking areas, efficiently capturing solar power to produce both thermal and photovoltaic energy. This provides a sustainable and eco-friendly energy solution, making solar one of the most extensively utilized renewable energy sources worldwide [9–12]. Recently, researchers have been actively working to enhance the efficiency of solar energy technologies, driven by their environmental benefits and lower installation and maintenance costs compared to other renewable energy systems. These technologies are generally divided into two categories: solar thermal systems, which utilize solar energy to generate heat [13], and solar photovoltaic systems, which convert solar energy directly into electricity [12].

2.1. Solar Photovoltaic Energy Technology

In recent years, the PV industry has seen remarkable growth, surpassing fossil fuel sources, driven by advancements in PV and wind technologies. This trend positions renewable energy to potentially meet over half of the world’s electricity demand by 2040 [14]. In addition, integrating advanced PV technologies such as perovskites and organic materials with traditional panels increases efficiency, making continuous innovation critical for sustainable development and the transition to a low-carbon economy [15]. Moreover, off-grid and microgrid systems utilizing distributed renewable energy sources, such as solar PV, provide practical solutions for delivering energy to rural and remote areas without access to the main grid [16]. These systems typically include solar panels, deep-cycle batteries, charge controllers, inverters, and other components that ensure a reliable power supply and effective energy distribution [17]. Solar photovoltaic (PV) systems have emerged as critical components in enhancing healthcare services in rural areas. Their applications can be categorized into several key domains, including providing reliable power for medical equipment, improving vaccine storage, facilitating telemedicine, and supporting general healthcare facility operations. However, their performance can be affected by weather conditions, and energy storage is required to address power intermittency. As shown in the schematic diagram below (Figure 1), photovoltaic systems are classified into the following categories based on their potential for integration with power grids [11].

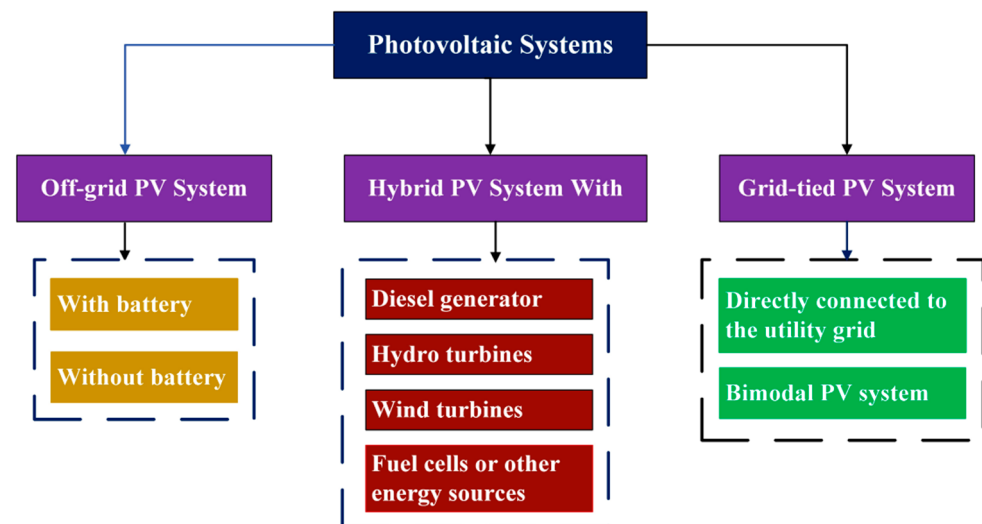


Figure 1. Types of photovoltaic systems.

Recent review articles on solar energy systems, as shown in (Table 1), highlight significant challenges to adopting solar systems in isolated rural areas, including high costs, limited public awareness, inadequate infrastructure, a lack of technical training, and policy gaps. Despite these barriers, solar technologies offer transformative potential, including improving healthcare resilience, enhancing rural electrification and quality of life, and reducing reliance on traditional energy sources, such as traditional diesel generator-based systems. Addressing financial, regulatory, and technical constraints through targeted policies and investments are essential for maximizing the benefits of solar energy, fostering sustainable development, and enhancing the quality of life in underserved, isolated rural communities.

Table 1. Recent review articles related to solar energy systems from the last five years.

Ref.	Objectives	Country	Remarks
[18]	Perspectives on solar PV system adoption in sub-Saharan Africa.	Malawi	Individuals have installed solar PV systems without adequate training, resulting in unsafe installations. This is a significant challenge in deploying solar energy in rural areas, where insufficient knowledge and training can endanger both the users and the systems.
[19]	Examine the factors affecting households' adoption of solar PV energy.	Uganda	The household head's income, acquisition method, and repayment terms positively affect the willingness to adopt solar energy for business use. Financial disclosure affects only the willingness to embrace solar energy.
[20]	Assess the public's understanding, knowledge, and attitudes toward solar technology.	Bangladesh	The study highlighted the need for collaboration among stakeholders to increase awareness and address adoption barriers such as cost and availability. This matched the challenges of deploying solar energy in rural areas, where limited awareness hindered adoption.

Table 1. *Cont.*

Ref.	Objectives	Country	Remarks
[21]	Addressing energy poverty: using climate finance to tackle the energy trilemma.	Indonesia	Transitioning to renewable energy sources is crucial but requires a substantial financial investment.
[22]	Develop a sustainable model to enhance the adoption of solar PV technology.	Tanzania	Limited financial access, insufficient enforcement of policies and regulations, technical constraints, low awareness, and the significant expense of solar PV systems poses a major challenge to their widespread adoption.
[23]	Techno-economic assessment of a standalone photovoltaic–diesel hybrid system.	Malaysia	It has a superior cost-effectiveness relative to traditional generator-based systems, decreased reliance on diesel, and improved electricity provision for rural communities.
[24]	Evaluate the readiness and challenges Malaysians face in adopting solar energy.	Malaysia	Major obstacles in implementing solar energy in rural areas include high upfront costs, limited public awareness, and efficiency that is dependent on weather conditions.
[25]	A techno-economic evaluation of off-grid solar PV systems.	Pakistan	Assessed the potential and economic feasibility of these systems for rural electrification, emphasizing the practical benefits of solar energy solutions.
[26]	Evaluate farmers' awareness and the factors influencing their adoption of solar-powered pumps.	-	The study found that perceived benefits and government incentives encourage using solar-powered pumps, while high costs and limited subsidy awareness deter adoption.
[27]	Evaluated the potential and analyzed solar PV energy systems.	Ethiopia	Solar energy potential of 5.52 kWh/m ² daily. The estimated daily electric loads are 313 Watt-hour (Wh) for a household, 2064 Wh for a school, and 2040 Wh for a clinic, with corresponding energy costs of 1.20 USD/kWh, 0.92 USD/kWh, and 0.87 USD/kWh, respectively. Long-term advantages and lower installation expenses compared to extending the national grid.
[28]	The review highlighted the potential of PV systems for providing decentralized electricity access.	Mozambique	Despite Africa's abundant solar resources, renewable energy accounts for only a small fraction of its total energy supply. Challenges such as high costs, insufficient infrastructure, and dependence on traditional energy sources like biomass for cooking underscore the difficulties in implementing solar energy in rural Africa.
[29]	Harnessing solar energy is crucial for addressing energy poverty in rural regions.	Pakistan	Energy poverty in rural areas subjects residents to various security risks, such as health hazards, fire accidents, time and financial constraints, illiteracy, and additional challenges. It underscored the necessity for policy recommendations directed at both the public and private sectors to address energy barriers, with a specific focus on implementing solar energy solutions in rural healthcare settings.

Table 1. *Cont.*

Ref.	Objectives	Country	Remarks
[30]	Developing a sustainable solar vaccine cold chain and vaccination program aims to promote clean energy in primary healthcare in Lebanon.	Lebanon	Solarizing Primary Health Care Centers (PHCCs) in Lebanon enhanced vaccine preservation and strengthened the resilience of health services. More than 1000 solar direct drive units were deployed across over 800 health facilities. Solarizing PHCCs improved vaccine preservation and boosted overall health service resilience. Challenges included geographic and structural limitations, as well as economic factors.
[31]	Energy status in Africa: challenges, advances, and sustainable solutions.	Sub-Saharan Africa	Rural electrification in sub-Saharan Africa struggles with limited modern energy access, dependence on non-eco-friendly sources, and inadequate infrastructure. Off-grid solutions, including solar mini-grids and home systems, can address these challenges, highlighting the need for effective policies, funding, and technology to optimize renewable energy in rural areas.
[32]	The political economy analysis of obstacles to rural electrification.	Tanzania	Institutional barriers to rural electrification in Tanzania demonstrate how political and regulatory factors can obstruct effective project implementation. Primary and secondary data identify key obstacles, such as non-independent institutions, policy gaps, and difficulties for governing bodies. A key challenge is the lack of political will and commitment, which impedes the implementation of large-scale solar power projects in rural areas.
[33]	Impact of solar lighting and electricity on maternity care quality and timeliness.	Uganda	Universal access to modern energy and the assurance of safe childbirth are vital global health priorities, but there is a lack of comprehensive research on their adoption and impact. Reliable lighting is essential for timely and effective healthcare, as it may improve providers' ability to promptly address and mitigate the risk of postpartum hemorrhage. The intervention was well-adopted, improved facility lighting, and modestly enhanced maternal care during deliveries.

2.2. Solar Thermal Energy Technology

Currently, the use of solar thermal technologies is rapidly increasing due to the scarcity of fossil fuels and the need for zero-emission energy. These technologies capture solar energy either directly or indirectly, converting solar radiation into heat energy. As renewable energy systems increasingly require energy storage solutions, the significance of thermal energy storage is growing across various technologies, capturing and storing heat for applications such as waste heat recovery, cooling heavy electronic equipment, solar water heating, solar drying, desalination, electricity for residential and commercial buildings, enhancing thermal comfort in heating, ventilation, and air conditioning (HVAC) systems, vapor absorption refrigeration, and various medical and agricultural uses [34–36]. Considering this growing demand, solar thermal power systems are attracting a growing global interest because they effectively utilize proven technologies and have demonstrated both

economic and technical viability [37]. Moreover, advanced materials are being developed to capture and store solar energy, and the development of effective and affordable energy storage technologies is crucial for the widespread adoption of solar power.

To this end, concentrated solar power plants incorporate thermal energy storage systems, which allow for reliable electricity generation and serve as a more economical alternative to battery-based storage solutions [38]. A solar collector captures thermal energy from solar radiation through absorption, with the stored energy then transferred by a circulating fluid for various specific applications. These collectors are classified into two primary types: non-tracking collectors, which maintain a fixed position, and tracking collectors, which adjust their orientation to follow the sun's movement; tracking collectors are further categorized into single-axis and dual-axis systems (Table 2).

Table 2. Categorizes solar collectors by operating temperature ranges, absorber types, and collector ratios [39,40].

Tracking	Type of Collector	Absorber Type	Temperature Range (°C)	Collector Ratio
Stationary	Flat plate collector	Flat	30 to 80	1
	Evacuated tube collector	Flat	50 to 200	1
	Compound parabolic	Tubular	60 to 240	1 to 5
One-axis	Fresnel lens		60 to 250	10 to 40
	Parabolic trough	Tubular	60 to 300	15 to 45
	Cylindrical trough		60 to 300	10 to 50
Two-axis	Parabolic dish reflector	Point	100 to 500	150 to 1500
	Heliostat field collector		150 to 2000	100 to 1000

Additionally, collectors are categorized by their working fluid: solar water heaters use water, while solar air heaters use air. A standard solar water heating system consists of a solar collector and a storage tank [40]. These systems are further classified into passive solar water heating (SWH) systems, which utilize thermosyphon action for fluid circulation without external pumps, and active SWH systems, which rely on pumps to move the fluid, as illustrated in Figure 2.

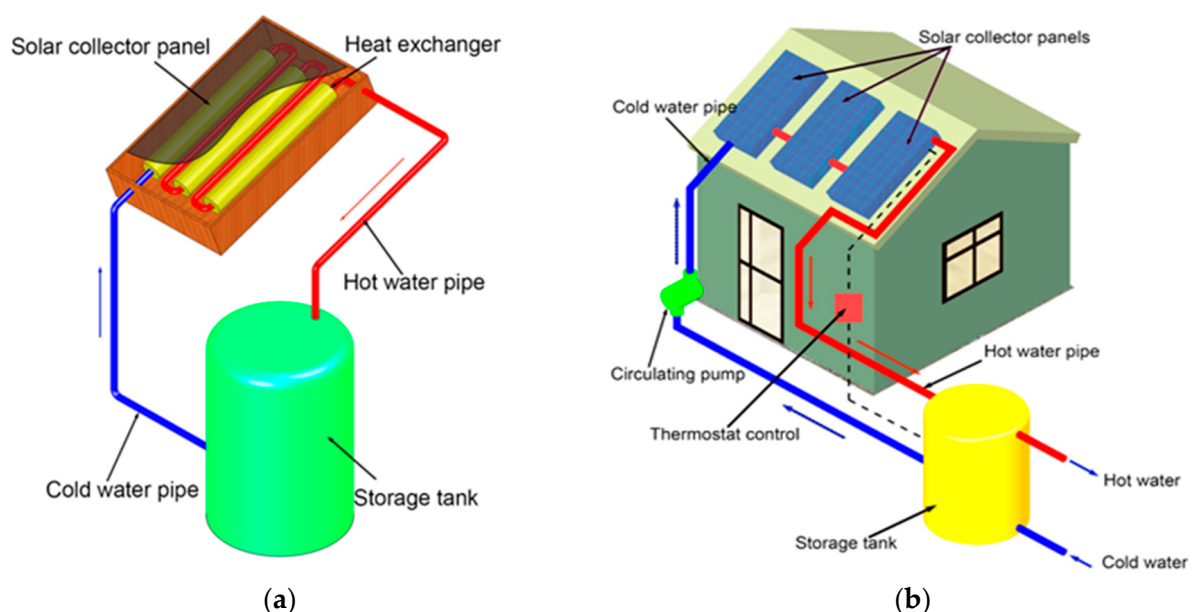


Figure 2. Solar water heating systems: (a) passive and (b) active.

Flat plate collectors, commonly used for low-temperature heating, feature a flat, rectangular box structure featuring a transparent cover and an internal black absorber plate and are favored for their simple design, ease of installation, and cost-effectiveness [41]. Evacuated tube solar collectors are an effective technology for solar thermal energy, especially in regions with varied climates. Their ability to maintain high temperatures and efficiency in various conditions makes them a popular option for solar water heating and other thermal application [42–44]. The schematic representations of flat plate and evacuated tube collectors are shown in Figure 3.

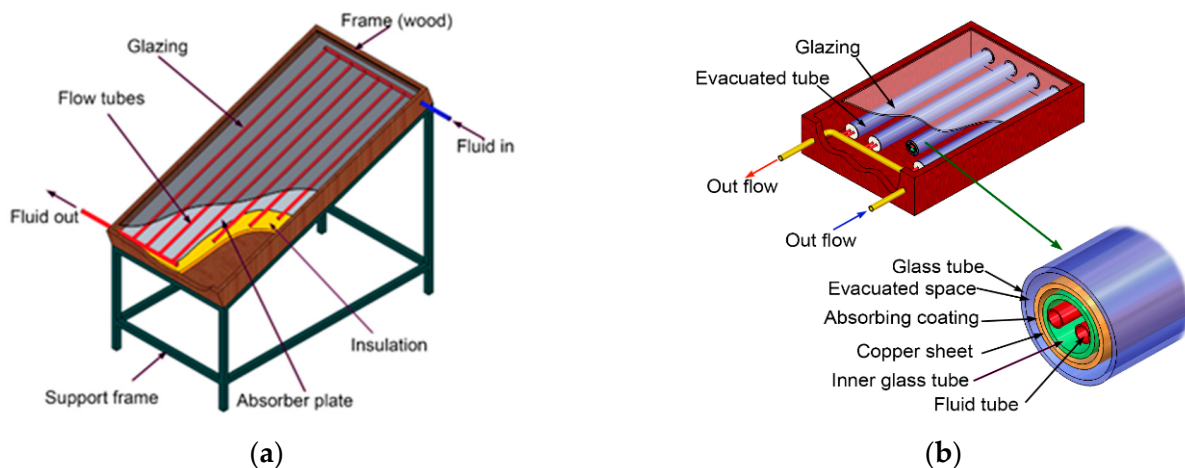


Figure 3. Flat plate collector (a) and (b) evacuated tube collector.

A Compound Parabolic Collector (CPC) utilizes a parabolic reflector to focus sunlight onto a receiver, making it well-suited for water heating and industrial applications [45]. CPCs provide significantly higher thermal efficiency compared to flat plate collectors, particularly when paired with advanced tracking systems [46]. Their extensive solar capture range and minimal alignment requirements increase their versatility across diverse locations. A Fresnel solar collector uses Fresnel lenses and prisms to efficiently focus sunlight onto a smaller area, thereby increasing solar energy capture [47]. It also improves the performance of systems such as solar cookers and photovoltaic systems by concentrating solar energy, which enhances the intensity of the captured solar radiation [48,49], and integrating Fresnel lenses with nanofluids has been investigated, leading to better thermal conversion efficiencies [50]. The schematic representations of compound parabolic and Fresnel solar collectors are shown in Figure 4a,b, respectively.

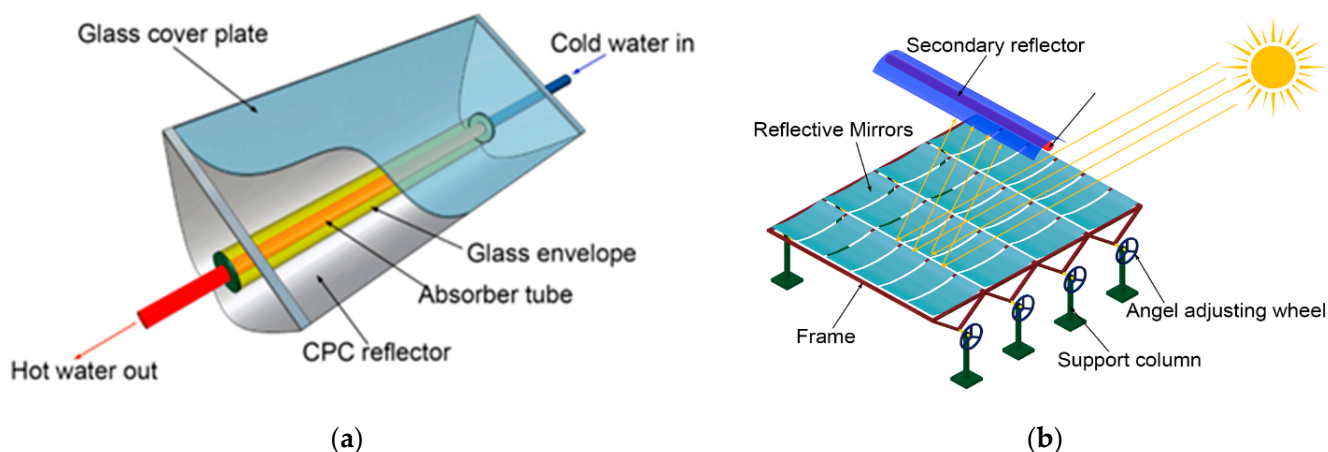


Figure 4. (a) Compound Parabolic Collector and (b) Fresnel solar collector.

The heliostat field solar collector is a key advancement in solar thermal technology for concentrated solar power systems. Improving its design and efficiency is vital for enhancing performance and cost-effectiveness, as these fields, which use mirrors to reflect sunlight onto a central receiver, account for 40% to 50% of total investment costs and can incur significant energy losses if not optimized [51], as shown in Figure 5.

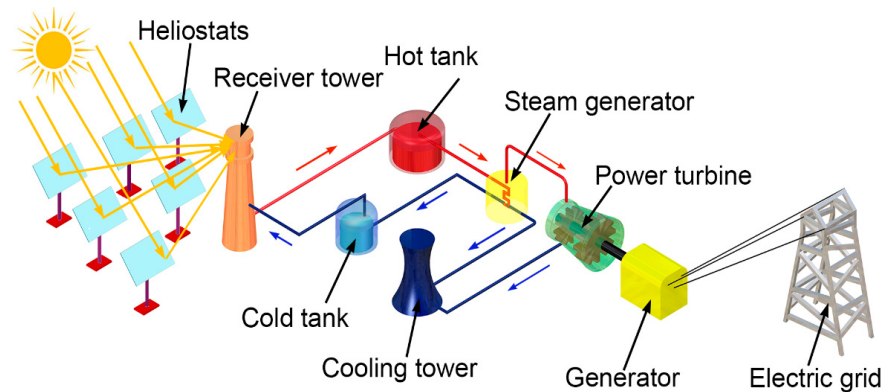


Figure 5. Heliostat field solar collector.

Parabolic dish solar reflectors are essential for solar energy applications, as they focus sunlight for heating, electricity generation, and chemical processes, as shown in Figure 6a. It employs a parabolic reflector to focus sunlight onto a receiver, converting the captured solar energy into thermal energy, which can subsequently be used to generate electricity, cooking, or industrial processes. Enhanced by a conical receiver design, solar dish collectors achieve average efficiencies ranging from 45% to 62%, depending on design and operating conditions [52]. In addition, parabolic trough collectors (PTCs) represent a significant advancement in CSP technology, recognized for their efficiency and versatility, utilizing parabolic reflectors to concentrate solar radiation onto a receiver tube, where a heat transfer fluid is heated for electricity generation or other thermal applications. This technology accounts for more than 80% of the total installed capacity in global CSP plants, demonstrating its widespread use and advanced development [53,54]. The efficiency of PTCs depends on various factors, such as precise alignment and the accuracy of the reflector shape; even minor misalignments can significantly reduce both optical and thermal performance [55], as shown in the schematic representation in Figure 6b.

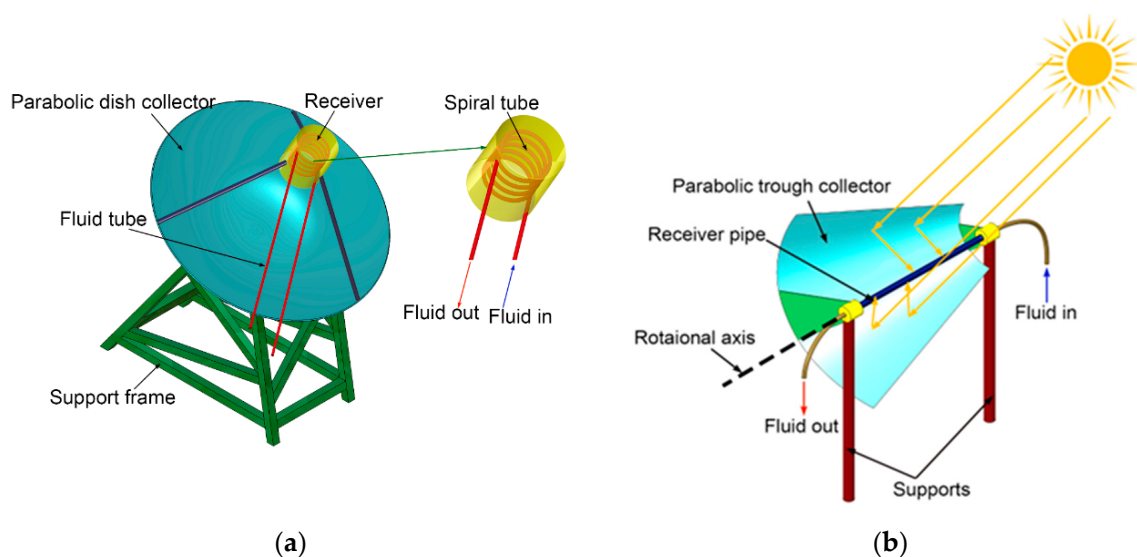


Figure 6. (a) Parabolic dish collector and (b) parabolic trough collector.

A new solar collector technology, known as hybrid photovoltaic–thermal, integrates both photovoltaic and solar thermal processes to enhance energy efficiency [56]. This system improves energy output by increasing the efficiency of photovoltaic conversion and simultaneously capturing solar heat. It produces electricity using photovoltaic cells and transforms solar energy into heat. Moreover, the combination of energy storage solutions with solar power systems has become increasingly prominent, with progress being made in battery technologies, pumped hydro storage, thermal storage, and other developing innovations [57].

In rural healthcare contexts, the integration of hybrid photovoltaic–thermal systems has the potential to deliver significant advantages compared to stand-alone photovoltaic or thermal systems. Hybrid photovoltaic–thermal systems can achieve total efficiencies of up to 60–70%, compared to stand-alone photovoltaic systems (15–22%) or thermal systems (40–70%). By integrating both the electrical conversion efficiency of solar cells and the heating capabilities of the thermal component, they are particularly suitable for rural healthcare settings [58,59], which require both electricity for medical equipment and hot water for cleaning, sterilization, and patient care. However, when comparing costs, hybrid photovoltaic–thermal systems have a higher initial capital and maintenance expenses, whereas traditional stand-alone PV systems are more economically viable and have been more widely adopted in many low-resource environments [59,60]. Figure 7 illustrates this system, showing photovoltaic cells positioned on one side of an absorber plate and a fluid channel for heating on the opposite side. In the case of water, copper pipes are attached to the absorber plate, while for air, a channel is incorporated between the absorber plate and the rear plate, resembling the structure of solar air heaters.

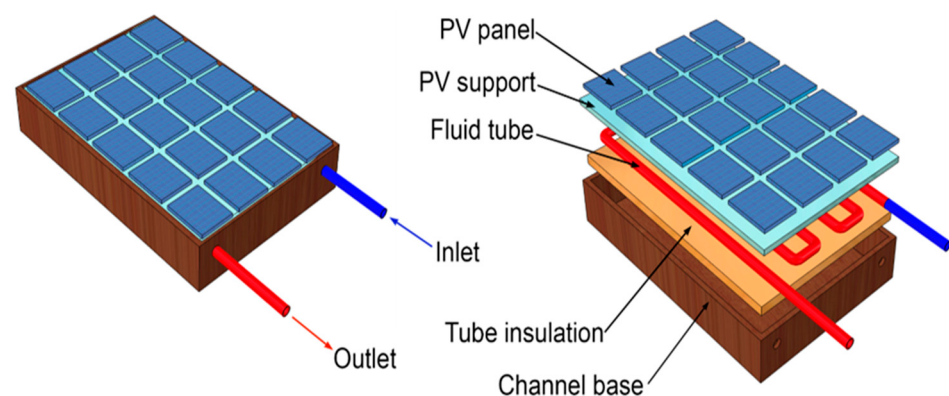


Figure 7. Hybrid photovoltaic–thermal collector.

3. Energy Storage Technologies

Importance and Role of Energy Storage: Energy storage technologies play a crucial role in modern energy systems, enhancing energy security, supporting renewable energy integration, and improving overall efficiency. As the global energy transition accelerates, storage solutions help mitigate the intermittency of renewable sources and ensure a stable power supply. These technologies also reduce costs and promote the wider adoption of clean energy solutions by enhancing grid stability and load management. Research advancements have led to significant improvements in energy storage materials and system efficiencies [61–65]. Notable developments include lithium-ion batteries, redox flow batteries, and molten salt energy storage, all of which facilitate the broader adoption of renewable energy by stabilizing the grid and managing energy fluctuations [61,66,67]. Additionally, breakthroughs in electrocatalysts for oxygen evolution reactions have further improved energy storage and conversion efficiencies [61].

Applications of Energy Storage: Energy storage applications span multiple sectors, including grid support, transportation, residential and commercial buildings, and industrial processes. In electricity grids, storage systems balance supply and demand, regulate frequency, and enable renewable energy integration. In transportation, batteries and fuel cells power electric and hybrid vehicles. In buildings, energy storage solutions lower peak electricity demand, provide backup power, and improve overall efficiency. In industrial settings, they support load management and enhance grid reliability. Solar thermal energy storage (STES) systems are particularly valuable for maintaining a steady energy supply, capturing excess solar energy during peak sunlight hours and releasing it when needed. Technologies such as phase change materials (PCMs) and thermal storage units have been explored to enhance STES performance [68,69]. For instance, paraffin-based PCMs improve solar thermal energy conversion efficiency, while molecular solar thermal storage systems using photochromic molecules present innovative solutions [70].

Thermal Energy Storage (TES) Technologies: Thermal energy storage (TES) technologies fall into three categories: sensible heat storage, latent heat storage, and thermochemical heat storage. Sensible heat storage, the most widely used method, utilizes affordable materials like water and concrete but requires a larger surface area, and latent heat storage offers higher energy density but may suffer from inefficient heat transfer. Thermochemical storage boasts the highest capacity but presents challenges in reactor design and durability [71]. These TES approaches are crucial for ensuring continuous electricity generation in concentrated solar power (CSP) plants and for seasonal energy storage [72]. Lithium-ion batteries (LIBs) have become a leading energy storage option due to their high energy density, long lifespan, and decreasing costs, making them particularly suitable for off-grid solar applications in healthcare settings [73,74]. While lead–acid batteries remain widely used for rural electrification due to their affordability, LIBs outperform them in efficiency and life-cycle cost [75].

Hybrid Systems: Hybrid renewable energy systems that combine solar photovoltaics with energy storage solutions, such as lithium-ion batteries and thermal storage, improve energy efficiency and reduce dependence on fossil fuels [76]. These systems help maintain critical healthcare services, such as vaccine refrigeration and sterilization, by ensuring an uninterrupted power supply. To maximize efficiency, advanced energy management techniques like maximum power point tracking (MPPT) optimize energy extraction from solar panels, improving battery charging efficiency [77,78]. Additionally, integrating battery management systems with the Internet of Things (IoT) enhances monitoring and maintenance, extending the battery's lifespan and performance [79]. Moreover, integrating multiple energy storage technologies, such as lithium-ion batteries, lead–acid batteries, and thermal energy storage, provides a robust approach to meeting energy needs in rural healthcare settings. Thermal storage solutions, including phase change materials and thermochemical systems, improve energy efficiency and reliability, particularly for applications like vaccine refrigeration, medical sterilization, and nighttime lighting in off-grid clinics [80,81]. These advancements collectively contribute to a more resilient, cost-effective, and sustainable healthcare infrastructure in rural areas. However, addressing economic barriers and policy limitations remains critical to maximizing the full potential of these energy storage technologies.

The classification of energy storage technologies, including TES, as shown in Figures 8 and 9, categorizes them based on the type of energy they store and illustrates these diverse approaches [61,82,83] and comparisons of different battery technologies (Table 3).

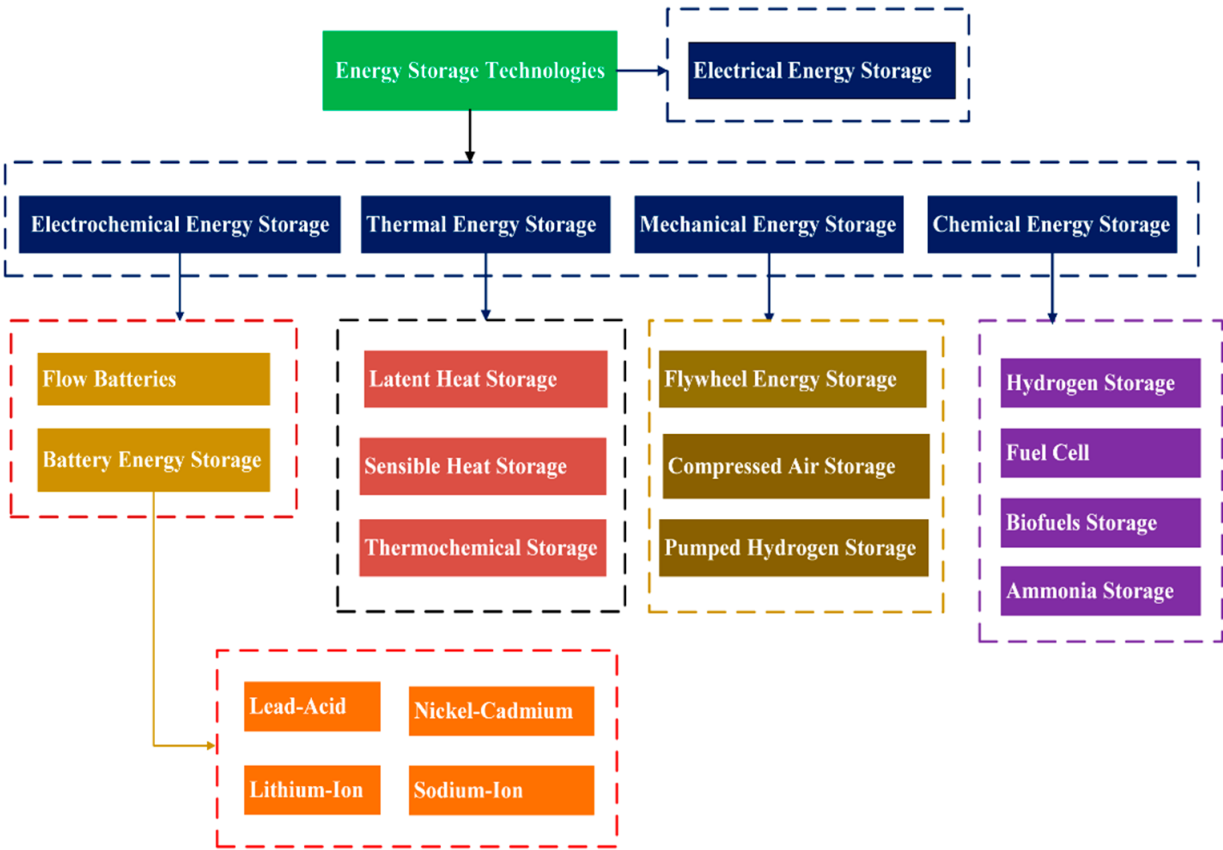


Figure 8. Classification of energy storage technologies.

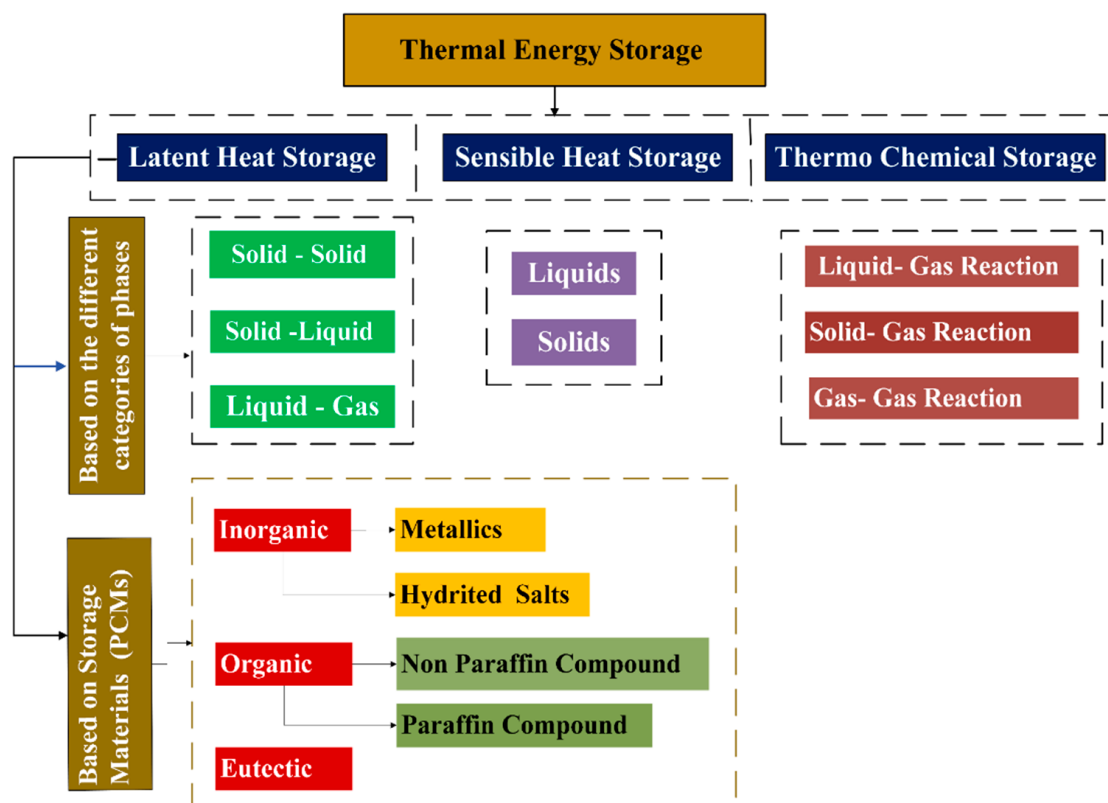


Figure 9. Classification of thermal energy storage.

Table 3. Comparison of different battery technologies [84].

Factors	Lead–Acid Battery	Lithium-ion Battery	Flow Battery
Performance (%)	75–80	80–86	60–70
Energy per unit mass (Wh/kg)	50–100	200–350	20–70
Specific power (W/kg)	10–500	100–350	-
Self-discharge rate (%)	0.1 to 0.4 daily	5 monthly	0.1 to 0.4 daily
Depth of discharge (%)	70	Up to 100	100
Installation power cost (EUR/kW)	150–200	150–200	1000–1500
Service life	500 to 2000	1000–5000 cycles	More than 10,000
Installation energy cost (EUR/kW)	100–250	3000–800	300–500
Service life (years)	5–15	5–20	10–15

4. Challenges of Energy Access in Rural Healthcare Systems

Technological Barriers: Developing nations face significant challenges in transitioning to renewable energy sources due to limited access to modern state-of-the-art technologies and inadequate funding for technological advancements in the renewable energy sector. Moreover, economic constraints, technological limitations, and policy barriers complicate this transition [85,86], resulting in a continued reliance on non-renewable energy sources and elevated carbon emissions [87].

Gender and Health Impacts: In addition to these systemic issues, inadequate energy access in rural areas disproportionately affects women and contributes to a lack of awareness about family planning. Limited availability of maternal healthcare services increases health risks during childbirth, while the absence of modern energy sources forces women to spend excessive time on household tasks and caregiving. Cooking with traditional fuels exacerbates respiratory diseases, causes eye irritation, and contributes to air pollution. Considering the effects on healthcare services, the lack of reliable electricity in rural facilities poses critical challenges, as essential medical devices such as sterilization machines, vaccine refrigerators, and diagnostic tools require consistent power to function effectively. Inconsistent electricity compromises patient care quality: inadequate lighting can hinder medical procedures during emergencies, and reliable communication systems are necessary for coordinating care. Electricity is also essential for water purification and pumping, ensuring hygiene and preventing infections [88]. Consequently, these energy access issues contribute to challenges in staff retention, as healthcare professionals are less likely to work in facilities without reliable power. According to the World Health Organization, in sub-Saharan Africa, retention rates in off-grid clinics are up to 60% lower than in fully electrified facilities, and nearly 1 billion people rely on clinics without reliable power, which negatively impacts healthcare quality and accessibility and limits the implementation of telemedicine and digital health technologies.

Operational Challenges: Compounding these difficulties, operational issues such as theft and inadequate maintenance further complicate efforts to electrify rural healthcare facilities. Hence, addressing these challenges requires a comprehensive approach that includes the investment in sustainable energy solutions, particularly solar power, improved infrastructure, and better coordination among stakeholders [89]. Implementing solar power systems can provide a sustainable energy source for rural healthcare facilities, enhancing both access and quality of care [90]. Engaging local communities in energy projects fosters a sense of ownership and improves maintenance [88].

Role of Policy: In addition, policy support from governments and non-governmental organizations (NGOs) is crucial for prioritizing electrification in rural healthcare as part of broader development objectives [90]. Ultimately, a holistic approach that combines technological progress, community participation, and supportive policies is essential for successfully addressing these challenges. The adoption of solar energy systems in remote rural health centers and clinics in developing countries is strongly influenced by socio-economic factors, such as income levels and government policies, which play a crucial role in determining the feasibility and long-term sustainability of these energy solutions. To begin with, income levels significantly affect the implementation of solar systems in rural households and healthcare facilities, which often operate with limited financial resources. This financial constraint makes the initial costs of solar installations a considerable obstacle. However, recent research shows that solar energy systems can become cost-effective in the long run by reducing the reliance on costly and unreliable fossil fuels, ultimately improving socio-economic conditions in isolated rural communities [25,91].

In addition, government policies have a substantial impact on the adoption of solar energy in rural health centers. Supportive initiatives such as solar energy subsidies, tax incentives, collaborations with international aid organizations, and investments in infrastructure can greatly enhance the success of solar energy projects [7,92]. A significant example is the healthcare initiative in Ghana and Uganda, where government and international collaborations effectively implemented solar energy to enhance healthcare services [93]. By enabling the operation of essential medical equipment, extending operating hours, and providing reliable vaccine storage through solar refrigeration, these initiatives contribute to better healthcare outcomes. Conversely, unclear policies or bureaucratic challenges can deter investment and slow the deployment of solar energy systems, as seen in the difficulties of integrating solar solutions into existing healthcare infrastructures [92]. The socio-economic benefits of solar energy adoption extend beyond electricity supply. Reliable energy access in rural health centers has been linked to improved healthcare services, particularly in maternal and child health [94,95].

5. Successful Solar Energy Implementations in Rural Healthcare

The implementation of solar energy in rural healthcare facilities has proven to be a game changer in addressing the persistent issue of unreliable electricity in developing countries. Many medical centers in remote areas struggle to maintain consistent power, which severely limits their ability to store vaccines, provide adequate lighting, and operate essential medical equipment. By offering a sustainable and renewable alternative, solar energy enhances healthcare resilience, improves service delivery, and fosters environmental sustainability. In addition, the long-term maintenance of solar infrastructure in local communities relies on robust training models and active community engagement. Key strategies include community-based maintenance, hands-on technical training, raising awareness about the benefits of solar energy, collective ownership models, public–private partnerships, local governance, and mobile-based monitoring, all of which support collaboration, shared decision-making, resilience, and ultimately the longevity of solar projects.

Moreover, the effective implementation of off-grid solar energy projects in the health sector of rural areas in developing countries depends on several critical success factors. These factors include technological, economic, social, and policy aspects, all of which contribute to the overall effectiveness and sustainability of solar energy initiatives.

Technological Suitability: Ensuring the right solar technologies are selected is crucial for effective implementation in rural healthcare settings. Photovoltaic systems, known for their scalability, have proven to be particularly effective in powering essential medical equipment, including vaccine refrigerators and diagnostic tools [95]. A continuous and

reliable power supply is essential, especially in emergencies [92], and integrating solar solutions with existing healthcare infrastructure significantly improves service availability, extends operational hours, and enhances patient care. Despite its many benefits, the high initial cost of solar installations remains a major challenge for rural communities. Reliability is also essential; solar energy solutions must provide a consistent power supply to allow health services to operate effectively, particularly during emergencies.

Economic Viability and Financial Sustainability: Economic factors are essential for the success of solar projects. High initial investment costs for solar home systems can be a significant hurdle for many rural communities. Financial models that incorporate subsidies, microfinancing, and community-driven ownership can help address this issue and promote sustainability [96]. Over time, solar energy reduces operational costs, allowing healthcare facilities to allocate resources more efficiently and generate long-term savings [95]. Additionally, surplus solar energy can support local economic activities, such as mobile phone charging and refrigeration, further strengthening community engagement and generating additional income [97].

Community Engagement and Capacity Building: Community involvement plays a critical role in the long-term success of solar energy projects. When local stakeholders are actively engaged in planning and maintaining these systems, they are more likely to ensure their continued functionality [92,98]. Training healthcare workers and local technicians in the operation and upkeep of solar infrastructure fosters self-sufficiency and reduces reliance on external support [99]. Moreover, including community members in decision-making processes allows energy solutions to be tailored to their specific needs, which significantly increases the chances of successful adoption and integration into existing health systems. By combining community involvement with capacity building, these projects create a sustainable framework that empowers local stakeholders and strengthens the resilience of health systems. This collaborative approach ensures that solar energy initiatives are integral parts of a comprehensive strategy focused on improving health outcomes, rather than isolated solutions.

Policy Support and Institutional Frameworks: Establishing supportive policy environments is vital for the effective implementation of solar energy projects, particularly in the healthcare sector. Government policies and institutional backing are also vital in promoting solar energy adoption in healthcare. Regulatory frameworks that encourage investment, simplify approval processes, and align renewable energy initiatives with broader health and development goals can significantly accelerate adoption [92,100]. For instance, Cuba's government-backed solar programs have successfully improved healthcare electrification in remote areas, demonstrating how policy-driven initiatives can create a widespread impact [101]. A study in Ghana demonstrated that solar-powered community health services significantly improved healthcare delivery by enabling essential services that were previously unavailable due to electricity shortages [97].

International organizations such as the United Nations Development Program and the United Nations International Children's Emergency Fund (UNICEF) provide essential technical assistance and funding to help nations implement effective policy frameworks that align with sustainable development and healthcare objectives [7]. Additionally, robust monitoring and evaluation systems are necessary to track the effectiveness of solar energy projects, identify areas for improvement, and optimize long-term healthcare outcomes.

A 2017 report from the United Nations Development Program showcased the impact of solar energy deployment, highlighting installations in approximately 1000 healthcare centers across 15 countries, including Malawi, Zimbabwe, Liberia, Namibia, and Zambia [102]. These initiatives have demonstrated how solar power can strengthen healthcare infrastructure, reduce operational costs, and enhance access to medical services. For in-

stance, the installed solar panels power the Sipape Rural Hospital in Bulawayo, Zimbabwe and Zambia, providing a consistent power supply needed for vaccine refrigerators and many life-saving medical devices. This helps ensure that healthcare workers can reduce complications, manage data without interruption, and provide continuous care during pregnancy and childbirth (Figure 10). However, while these installed solar energy projects report overall benefits, they often lack statistical data on percentage improvements in service delivery and operational sustainability, thereby indicating a gap that future research should address.



Figure 10. Solar panels installed at rural hospitals in Zimbabwe and Zambia [103]: (a) Solar panels powering the rural hospital in Bulawayo, Zimbabwe; (b) a healthcare professional delivers a baby at Chongwe District Hospital, Zambia; (c) keeping data secure without power interruptions at Sipape Rural Hospital in Bulawayo, Zimbabwe; and (d) a fetal heart rate monitor assisting a mother at Chongwe District Hospital, Lusaka Province, Zambia.

6. Conclusions

Renewable energy sources, particularly solar power encompassing both concentrating solar power and solar photovoltaic systems, are receiving increasing global attention as promising solutions for future electricity generation. This review underscores the role of solar energy in strengthening rural healthcare systems in developing countries, based on a systematic peer-reviewed literature search, while acknowledging the limitation of English-language source restriction.

The present review study explores the transformative potential of solar energy in improving healthcare systems in rural areas of developing countries, where access to reliable electricity is often limited. By providing a sustainable, cost-effective, and eco-friendly solution, solar energy enables the continuous operation of critical healthcare equipment, enhances patient care, and reduces dependence on fossil fuels through reliable 24 h electrification.

Recent advancements in solar energy technologies, such as photovoltaic and solar thermal systems, have significantly improved the affordability and accessibility of solar energy. Off-grid solar systems, including microgrids and battery storage solutions, have further expanded the reach of clean energy to remote areas. To fully unlock the potential of solar energy, governments, non-governmental organizations, and the private sector must collaborate to ensure financial accessibility and promote capacity-building initiatives in local communities. Solar energy offers a practical and scalable solution for bridging the energy gap in rural healthcare.

Despite these benefits, challenges such as high installation costs, a lack of technical training, and policy barriers hinder widespread adoption. Targeted investments, government incentives, and community engagement are essential for overcoming these obstacles. By integrating solar energy into rural healthcare infrastructure, nations can enhance medical services, promote environmental sustainability, and achieve key Sustainable Development Goals (SDGs).

Future research should focus on developing cost-effective systems that combine solar photovoltaic and thermal technologies, creating policy-driven frameworks and financial models to support scalable deployment, enhancing community-based training and maintenance programs to ensure long-term sustainability, and exploring digital solutions such as the Internet of Things (IoT) and smart sensors for the remote monitoring and maintenance of solar-powered healthcare facilities, which have a promising future.

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Abbreviations

The following abbreviations are used in this manuscript:

CPC	Compound Parabolic Collector
IEA	International Energy Agency
LIB	Lithium-Ion Battery
PCM	Phase Change Material
PTC	Parabolic Trough Collector
PV	Photovoltaic
SDG	Sustainable Development Goal
STES	Solar Thermal Energy Storage
SWH	Solar Water Heating

References

1. Bond, T.C.; Sun, K. Can reducing black carbon emissions counteract global warming? *Environ. Sci. Technol.* **2005**, *39*, 5921–5926. [[CrossRef](#)] [[PubMed](#)]
2. Almeshqab, F.; Ustun, T.S. Lessons learned from rural electrification initiatives in developing countries: Insights for technical, social, financial and public policy aspects. *Renew. Sustain. Energy Rev.* **2019**, *102*, 35–53. [[CrossRef](#)]

3. World Health Statistics 2023: Monitoring Health for the SDGs, Sustainable Development Goals. Available online: <https://www.who.int/publications/i/item/9789240074323> (accessed on 13 May 2025).
4. Adair-Rohani, H.; Zukor, K.; Bonjour, S.; Wilburn, S.; Kuesel, A.C.; Hebert, R.; Fletcher, E.R. Limited Electricity Access in Health Facilities of Sub-Saharan Africa: A Systematic Review of Data on Electricity Access, Sources, and Reliability. *Glob. Health Sci. Pract.* **2013**, *1*, 249–261. [[CrossRef](#)] [[PubMed](#)]
5. Kolosok, S.; Myroshnychenko, I.; Mishenina, H.; Yarova, I. Renewable energy innovation in Europe: Energy efficiency analysis. *E3S Web Conf.* **2021**, *234*, 21. [[CrossRef](#)]
6. Zahedi, R.; Zahedi, A.; Ahmadi, A. Strategic Study for Renewable Energy Policy, Optimizations and Sustainability in Iran. *Sustainability* **2022**, *14*, 2418. [[CrossRef](#)]
7. Sharma, L.; Singh, J.; Dhiman, R.; Nunez, D.R.V.; Ba, A.E.; Joshi, K.J.; Modi, B.; Padhi, A.; Tandon, J.K.; Seidel, M. Advancing Solar Energy for Primary Healthcare in Developing Nations: Addressing Current Challenges and Enabling Progress Through UNICEF and Collaborative Partnerships. *Cureus* **2024**, *16*, e51571. [[CrossRef](#)] [[PubMed](#)]
8. Kraus, S.; Breier, M.; Dasí-Rodríguez, S. The art of crafting a systematic literature review in entrepreneurship research. *Int. Entrep. Manag. J.* **2020**, *16*, 1023–1042. [[CrossRef](#)]
9. Jamar, A.; Majid, Z.A.A.; Azmi, W.H.; Norhafana, M.; Razak, A.A. A review of water heating system for solar energy applications. *Int. Commun. Heat Mass Transf.* **2016**, *76*, 178–187. [[CrossRef](#)]
10. Kristiawan, H.; Kumara, I.N.S.; Giriantari, I.A.D. Potensi Pembangkit Listrik Tenaga Surya Atap Gedung Sekolah di Kota Denpasar. *J. Spektr.* **2019**, *6*, 66. [[CrossRef](#)]
11. El Hammoumi, A.; Chtita, S.; Motahhir, S.; El Ghzizal, A. Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar trackers and floating solar panels. *Energy Rep.* **2022**, *8*, 11992–12010. [[CrossRef](#)]
12. Hassoune, H.; Zohra, M.B.; Riad, A.; Alhamanyi, A. Improving electrical energy and producing thermal energy in solar photovoltaic system by integrating phase change materials. *E3S Web Conf.* **2021**, *297*, 01021. [[CrossRef](#)]
13. Nkele, A.; Ikhiya, I.; Chime, C.; Ezema, F. Improving the Performance of Solar Thermal Energy Storage Systems. *J. Energy Power Technol.* **2023**, *5*, 24. [[CrossRef](#)]
14. Huang, G.; Tang, Y.; Chen, X.; Chen, M.; Jiang, Y. A Comprehensive Review of Floating Solar Plants and Potentials for Offshore Applications. *J. Mar. Sci. Eng.* **2023**, *11*, 2064. [[CrossRef](#)]
15. Muñoz, R.; del Coso, R.; Nuño, F.; Villegas, P.J.; Álvarez, D.; Martínez, J.A. Solar-Powered Smart Buildings: Integrated Energy Management Solution for IoT-Enabled Sustainability. *Electronics* **2024**, *13*, 317. [[CrossRef](#)]
16. De Almeida, A.T.; Moura, P.S. Off-grid appliances and smart controls for energy access. *Energy Effic.* **2020**, *13*, 193–195. [[CrossRef](#)]
17. Bello, R.; Suleiman, T.; Kende, U.A.; Abulrasheed, M. Design Analysis of 7.5KW Stand Alone Solar Photovoltaic Power System for an Intermediate Household. *Asian J. Res. Rev. Phys.* **2021**, *5*, 18–25. [[CrossRef](#)]
18. Ngonda, T.; Nkhoma, R.; Ngonda, V. Perceptions of Solar Photovoltaic System Adopters in Sub-Saharan Africa: A Case of Adopters in Ntchisi, Malawi. *Energies* **2023**, *16*, 7350. [[CrossRef](#)]
19. Nabaweesi, J.; Kabuye, F.; Adaramola, M.S. Households' willingness to adopt solar energy for business use in Uganda. *Int. J. Energy Sect. Manag.* **2024**, *18*, 26–42. [[CrossRef](#)]
20. Emon, M.M.H. Unveiling the Progression Towards Solar Power Adoption: A Comprehensive Analysis of Understanding, Awareness, and Acceptance of Solar Technology in Bangladesh. *Econ. Growth Environ. Sustain.* **2023**, *2*, 105–111. [[CrossRef](#)]
21. Setyowati, A.B. Mitigating energy poverty: Mobilizing climate finance to manage the energy trilemma in Indonesia. *Sustainability* **2020**, *12*, 1603. [[CrossRef](#)]
22. Raymond, J.; Kihedu, J.H.; Kimambo, C.Z.M. A Model for Sustainable Adoption of Solar Photovoltaic Technology in Tanzania. *Tanzan. J. Eng. Technol.* **2022**, *41*, 16–34. [[CrossRef](#)]
23. Harmen, M.; Julai, N.; Othman, A.K.; Aznan, H.; Kulanthavel, G. Techno-economic Analysis of a Stand-alone Photovoltaic-Diesel Hybrid System for Rural Area in Sarawak. *Int. J. Integr. Eng.* **2020**, *12*, 137–147. [[CrossRef](#)]
24. Jing, K.T.; Qing, C.T.; Yee, H.C. Readiness of Malaysian on Sustainable Development in Solar Energy Application. *Int. J. Sustain. Constr. Eng. Technol.* **2023**, *14*, 189–201. [[CrossRef](#)]
25. Irfan, M.; Zhao, Z.Y.; Ahmad, M.; Rehman, A. A techno-economic analysis of off-grid solar PV system: A case study for Punjab Province in Pakistan. *Processes* **2019**, *7*, 708. [[CrossRef](#)]
26. Kumar, V.; Syan, A.S.; Kaur, A.; Hundal, B.S. Determinants of farmers' decision to adopt solar powered pumps. *Int. J. Energy Sect. Manag.* **2020**, *14*, 707–727. [[CrossRef](#)]
27. Woldegiyorgis, T.A. Analysis of Solar PV Energy Systems for Rural Villages of Nekemte Area, Oromiya Region, Ethiopia. *J. Mod. Mater.* **2019**, *6*, 13–22. [[CrossRef](#)]

28. Santos, M.M.; Ferreira, A.T.V.; Lanzinha, J.C.G. Overview of Energy Systems in Africa: A Comprehensive Review. *Solar* **2023**, *3*, 638–649. [\[CrossRef\]](#)
29. Batool, K.; Zhao, Z.Y.; Atif, F.; Dilanchiev, A. Nexus Between Energy Poverty and Technological Innovations: A Pathway for Addressing Energy Sustainability. *Front. Environ. Sci.* **2022**, *10*, 888080. [\[CrossRef\]](#)
30. Kapuria, B.; Hamadeh, R.S.; Mazloun, F.; Korbane, J.A.; Aung, K.; Kamal, D.; Chamoun, N.; Syed, S. Achieving sustainable, environmentally viable, solarized vaccine cold chain system and vaccination program—An effort to move towards clean and green energy-driven primary healthcare in Lebanon. *Front. Health Serv.* **2024**, *4*, 1386432. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Agoundedemba, M.; Kim, C.K.; Kim, H.G. Energy Status in Africa: Challenges, Progress and Sustainable Pathways. *Energies* **2023**, *16*, 7708. [\[CrossRef\]](#)
32. Rugaimukamu, K.; Shauri, N.E.; Mazigwa, R.C. The Political Economy Analysis of Institutional Barriers to Rural Electrification in Tanzania. *Open J. Soc. Sci.* **2023**, *11*, 275–310. [\[CrossRef\]](#)
33. Rokicki, S.; Mwesigwa, B.; Waiswa, P.; Cohen, J. Impact of Solar Light and Electricity on the Quality and Timeliness of Maternity Care: A Stepped-Wedge Cluster-Randomized Trial in Uganda. *Glob. Health Sci. Pract.* **2018**, *9*, 777–792. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Shoeibi, S.; Kargarsharifabad, H.; Rahbar, N.; Khosravi, G.; Sharifpur, M. An integrated solar desalination with evacuated tube heat pipe solar collector and new wind ventilator external condenser. *Sustain. Energy Technol. Assess.* **2022**, *50*, 101857. [\[CrossRef\]](#)
35. Kumar, K.R.; Chaitanya, N.V.V.K.; Kumar, N.S. Solar thermal energy technologies and its applications for process heating and power generation—A review. *J. Clean. Prod.* **2021**, *282*, 125296. [\[CrossRef\]](#)
36. Chavan, S.; Rudrapati, R.; Manickam, S. A comprehensive review on current advances of thermal energy storage and its applications. *Alex. Eng. J.* **2022**, *61*, 5455–5463. [\[CrossRef\]](#)
37. Zhao, R.; Zhao, L.; Deng, S.; Zheng, N. Trends in patents for solar thermal utilization in China. *Renew. Sustain. Energy Rev.* **2015**, *52*, 852–862. [\[CrossRef\]](#)
38. Carrillo, A.J.; Bayon, A.; Coronado, J.M.; Mastronardo, E. Editorial: Recent Advances in Solar-Driven Thermochemical Fuel Production and Thermal Energy Storage. *Front. Energy Res.* **2022**, *10*, 885894. [\[CrossRef\]](#)
39. Kalogirou, S. The potential of solar industrial process heat applications. *Appl. Energy* **2003**, *76*, 337–361. [\[CrossRef\]](#)
40. Suman, S.; Khan, M.K.; Pathak, M. Performance enhancement of solar collectors—A review. *Renew. Sustain. Energy Rev.* **2015**, *49*, 192–210. [\[CrossRef\]](#)
41. Mustafa, J.; Alqaed, S.; Kalbasi, R. Challenging of using CuO nanoparticles in a flat plate solar collector- Energy saving in a solar-assisted hot process stream. *J. Taiwan Inst. Chem. Eng.* **2021**, *124*, 258–265. [\[CrossRef\]](#)
42. Naik, B.K.; Muthukumar, P. Performance assessment of evacuated U-tube solar collector: A numerical study. *Sādhanā* **2019**, *44*, 23. [\[CrossRef\]](#)
43. Selvakumar, P.; Somasundaram, P.; Tamilvanan, A.; Karthikeyan, R.; Rajagopal, T. Performance of P1 model in the prediction of static temperature and velocity magnitude of therminol D-12 in an evacuated tube solar collector. *Int. J. Innov. Technol. Explor. Eng.* **2019**, *8*, 255–261. [\[CrossRef\]](#)
44. Maraj, A.; Londo, A.; Firat, C.; Gebremedhin, A. Comparison of the energy performance between flat-plate and heat pipe evacuated tube collectors for solar water heating systems under mediterranean climate conditions. *J. Sustain. Dev. Energy Water Environ. Syst.* **2019**, *7*, 87–100. [\[CrossRef\]](#)
45. Yurchenko, V.; Yurchenko, E.; Çiydem, M.; Totuk, O. Ray tracing for optimization of compound parabolic concentrators for solar collectors of enclosed design. *Turk. J. Electr. Eng. Comput. Sci.* **2015**, *23*, 1761–1768. [\[CrossRef\]](#)
46. Riaz, H.; Ali, M.; Akhtar, J.; Muhammad, R.; Kaleem, M. Comparative Optical and Thermal Analysis of Compound Parabolic Solar Collector with Fixed and Variable Concentration Ratio. *Eng. Proc.* **2022**, *12*, 85. [\[CrossRef\]](#)
47. Berwal, S.; Khatri, N.; Kim, D. Fresnel lens-based solar concentrators. *Women Opt. Photonics India* **2023**, *12638*, 12–14. [\[CrossRef\]](#)
48. Asrori, A.; Udianto, P.; Faizal, E.; Rizza, M.A.; Witono, K.; Perdana, D. The Potential of Steam Generating by the PMMA Fresnel Lens Concentrator for Indoor Solar Cooker Application. *Period. Polytech. Mech. Eng.* **2024**, *68*, 120–129. [\[CrossRef\]](#)
49. Asrori, A.; Suparman, S.; Wahyudi, S.; Widhiyanuriyawan, D. An Experimental Study of Solar Cooker Performance with Thermal Concentrator System by Spot Fresnel Lens. *East.-Eur. J. Enterp. Technol.* **2020**, *5*, 31–41. [\[CrossRef\]](#)
50. Pandi, K.; Venkatachalapathy, S.; Suresh, S. Experimental investigation on low concentration nanofluids with Fresnel lens and evacuated tubes for solar applications. *Int. J. Appl. Ceram. Technol.* **2022**, *19*, 2236–2248. [\[CrossRef\]](#)
51. Cruz, N.C.; Salhi, S.; Redondo, J.L.; Álvarez, J.D.; Berenguel, M.; Ortigosa, P.M. Design of a parallel genetic algorithm for continuous and pattern-free heliostat field optimization. *J. Supercomput.* **2019**, *75*, 1268–1283. [\[CrossRef\]](#)
52. Subramani, J.; Nagarajan, P.K.; Subramaniyan, C.; Anbuselvan, N. Performance studies on solar parabolic dish collector using conical cavity receiver for community heating applications. *Mater. Today Proc.* **2021**, *45*, 1862–1866. [\[CrossRef\]](#)
53. Hamada, M.A.; Ehab, A.; Khalil, H.; Al-sood, M.M.A.; Kandeal, A.W.; Sharshir, S. Factors affecting the performance enhancement of a parabolic trough collector utilizing mono and hybrid nanofluids: A mini review of recent progress and prospects. *J. Contemp. Technol. Appl. Eng.* **2022**, *1*, 49–61. [\[CrossRef\]](#)

54. Wang, Q.; Shen, B.; Huang, J.; Yang, H.; Pei, G.; Yang, H. A spectral self-regulating parabolic trough solar receiver integrated with vanadium dioxide-based thermochromic coating. *Appl. Energy* **2021**, *285*, 116453. [\[CrossRef\]](#)
55. Natraj; Reddy, K.S.; Rao, B.N. Investigation of Variable Wind Loads and Shape Accuracy of Reflectors in Parabolic Trough Collector. *ASPS Conf. Proc.* **2022**, *1*, 1495–1504. [\[CrossRef\]](#)
56. Li, W.; Bu, F.; Shi, G.; Yuan, B.; Zhao, Y. Planning and design of an architectural energy supply system based on photovoltaic-thermal technology. *J. Phys. Conf. Ser.* **2024**, *2757*, 012007. [\[CrossRef\]](#)
57. Hasan, M.M.; Hossain, S.; Mofijur, M.; Kabir, Z.; Badruddin, I.A.; Yunus Khan, T.M.; Jassim, E. Harnessing Solar Power: A Review of Photovoltaic Innovations, Solar Thermal Systems, and the Dawn of Energy Storage Solutions. *Energies* **2023**, *16*, 6456. [\[CrossRef\]](#)
58. Barbu, M.; Siroux, M.; Darie, G. Performance Analysis and Comparison of an Experimental Hybrid PV, PVT and Solar Thermal System Installed in a Preschool in Bucharest, Romania. *Energies* **2023**, *16*, 5321. [\[CrossRef\]](#)
59. Aguilar-Jiménez, J.A.; Velázquez-Limón, N.; Islas-Pereda, S.; Ríos-Arriola, J.; Suástegui-Macias, J.A.; Cásaes-De la Torre, C.A.; Gómez-Hernandez, J.A. Technical and economic assessment of hybrid PVT solar systems compared to independent solar thermal and photovoltaic collectors in high-temperature zones: A case study in Mexicali, Mexico. *Renew. Energy* **2024**, *2*, 27533735241278104. [\[CrossRef\]](#)
60. Okoye, C.O.; Oranekwu-Okoye, B.C. Economic feasibility of solar PV system for rural electrification in Sub-Sahara Africa. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2537–2547. [\[CrossRef\]](#)
61. Wu, T.; Wang, J.W.; Qu, S.; Mi, Z.; Wei, Y.M. Frontiers of Energy Storage Technologies. *Int. J. Energy Res.* **2023**, *2023*, 7138669. [\[CrossRef\]](#)
62. Song, F.; Bai, L.; Moysiadou, A.; Lee, S.; Hu, C.; Liardet, L.; Hu, X. Transition Metal Oxides as Electrocatalysts for the Oxygen Evolution Reaction in Alkaline Solutions: An Application-Inspired Renaissance. *J. Am. Chem. Soc.* **2018**, *140*, 7748–7759. [\[CrossRef\]](#) [\[PubMed\]](#)
63. Yao, L.; Yang, B.; Cui, H.; Zhuang, J.; Ye, J.; Xue, J. Challenges and progresses of energy storage technology and its application in power systems. *J. Mod. Power Syst. Clean Energy* **2016**, *4*, 519–528. [\[CrossRef\]](#)
64. Mongird, K.; Viswanathan, V.; Balducci, P.; Alam, J.; Fotedar, V.; Koritarov, V.; Hadjerioua, B. An evaluation of energy storage cost and performance characteristics. *Energies* **2020**, *13*, 3307. [\[CrossRef\]](#)
65. Wang, P.; Yang, X.; Zhang, Q. Physical Energy Storage Technologies: Basic Principles, Parameters and Applications. *Highlights Sci. Eng. Technol.* **2022**, *3*, 73–84. [\[CrossRef\]](#)
66. Chen, S.; Xie, J. Application Prospect Analysis of Molten Salt Energy Storage Technology. *Highlights Sci. Eng. Technol.* **2022**, *26*, 46–51. [\[CrossRef\]](#)
67. Wang, Q.; Tan, Z.; De, G.; Pu, L.; Wu, J. Research on promotion incentive policy and mechanism simulation model of energy storage technology. *Energy Sci. Eng.* **2019**, *7*, 3147–3159. [\[CrossRef\]](#)
68. Choudhary, S.; Sumita, S.; Kumar, M.; Bairwa, S.; Soni, N. A Comprehensive Review on Enhancing Heat Transfer Rate and Innovation Design of a Heat Exchanger with Phase Change Material for Storing Solar Thermal Energy. *Int. J. Res. Publ. Rev.* **2024**, *5*, 3083–3086. [\[CrossRef\]](#)
69. Fan, D.; Meng, Y.; Jiang, Y.; Qian, S.; Liu, J.; Xu, Y.; Xiong, D.; Cao, Y. Silver/polypyrrole-functionalized polyurethane foam embedded phase change materials for thermal energy harvesting. *Nanomaterials* **2021**, *11*, 3011. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Mogensen, J.; Christensen, O.; Kilde, M.D.; Abildgaard, M.; Metz, L.; Kadziola, A.; Jevric, M.; Mikkelsen, K.V.; Nielsen, M.B. Molecular Solar Thermal Energy Storage Systems with Long Discharge Times Based on the Dihydroazulene/Vinylheptafulvene Couple. *Eur. J. Org.* **2019**, *2019*, 1986–1993. [\[CrossRef\]](#)
71. Pachori, H.; Choudhary, T.; Sheorey, T. Significance of thermal energy storage material in solar air heaters. *Mater. Today Proc.* **2022**, *56*, 126–134. [\[CrossRef\]](#)
72. Li, Z.; Xu, M.; Huai, X.; Huang, C.; Wang, K. Simulation and analysis of thermochemical seasonal solar energy storage for district heating applications in China. *Int. J. Energy Res.* **2021**, *45*, 7093–7107. [\[CrossRef\]](#)
73. Chen, T.; Jin, Y.; Lv, H.; Yang, A.; Liu, M.; Chen, B.; Xie, Y.; Chen, Q. Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems. *Transact. Tianjin Univ.* **2020**, *26*, 208–217. [\[CrossRef\]](#)
74. Puranik, S.; Hoffmann, M.M.; Farrukh, F.; Sharma, S. Optimal investments into rooftop solar and batteries for a distribution grid company and prosumers: A case study in India. In Proceedings of the 2022 IEEE 7th International Energy Conference (ENERGYCON), Riga, Latvia, 9–12 May 2022. [\[CrossRef\]](#)
75. Dorel, S.; Osman, M.G.; Strejoiu, C.V.; Lazaroiu, G. Exploring Optimal Charging Strategies for Off-Grid Solar Photovoltaic Systems: A Comparative Study on Battery Storage Techniques. *Batteries* **2023**, *9*, 470. [\[CrossRef\]](#)
76. Suresh, C.; Saini, R.P. Review on solar thermal energy storage technologies and their geometrical configurations. *Int. J. Energy Res.* **2020**, *44*, 4163–4195. [\[CrossRef\]](#)

77. Salman, S.; Ai, X.; Wu, Z. Design of a P-&O algorithm based MPPT charge controller for a stand-alone 200W PV system. *Prot. Control Mod. Power Syst.* **2018**, *3*, 25. [\[CrossRef\]](#)
78. Shiau, J.K.; Wei, Y.C.; Lee, M.Y. Fuzzy controller for a voltage-regulated solar-powered MPPT system for hybrid power system applications. *Energies* **2015**, *8*, 3292–3312. [\[CrossRef\]](#)
79. Liu, Y.; Bai, W.; Hong, G.; Zhang, W.; Yue, H. Design of Photovoltaic Centralized Management System for Storage Batteries Based on Internet of Things. In Proceedings of the 2019 International Conference on Wireless Communication, Network and Multimedia Engineering (WCNME 2019), Guilin, China, 21–22 April 2019.
80. Olatomiwa, L.; Sadiq, A.A.; Longe, O.M.; Ambafi, J.G.; Jack, K.E.; Abd'azeez, T.A.; Adeniyi, S. An Overview of Energy Access Solutions for Rural Healthcare Facilities. *Energies* **2022**, *15*, 9554. [\[CrossRef\]](#)
81. Falama, R.Z.; Skarka, W.; Doka, S.Y. Optimal Design and Comparative Analysis of a PV/Mini-Hydropower and a PV/Battery Used for Electricity and Water Supply. *Energies* **2023**, *16*, 307. [\[CrossRef\]](#)
82. Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl. Energy* **2015**, *137*, 511–536. [\[CrossRef\]](#)
83. Kampouris, K.P.; Drosou, V.; Karytsas, C.; Karagiorgas, M. Energy storage systems review and case study in the residential sector. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *410*, 012033. [\[CrossRef\]](#)
84. Elalfy, D.A.; Gouda, E.; Kotb, M.F.; Bureš, V.; Sedhom, B.E. Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends. *Energy Strategy Rev.* **2024**, *54*, 101482. [\[CrossRef\]](#)
85. Al-Rawi, O.F.; Bicer, Y.; Al-Ghamdi, S.G. Sustainable solutions for healthcare facilities: Examining the viability of solar energy systems. *Front. Energy Res.* **2023**, *11*, 1220293. [\[CrossRef\]](#)
86. Munjer, M.A.; Hasan, M.Z.; Hossain, M.K.; Rahman, M.F. The Obstruction and Advancement in Sustainable Energy Sector to Achieve SDG in Bangladesh. *Sustainability* **2023**, *15*, 3913. [\[CrossRef\]](#)
87. Mahmud, A. The impact of Islamic financial development on renewable energy production in Islamic countries. *Asian J. Islam. Manag. AJIM* **2023**, *2023*, 54–68. [\[CrossRef\]](#)
88. World Health Organization. *Energizing Health: Accelerating Electricity Access in Health-Care Facilities*; World Health Organization: Geneva, Switzerland, 2023.
89. Imasiku, K. Comprehensive approaches to electrifying rural health facilities: Integrating renewable energy and financial mechanisms in Sub-Saharan Africa. *Energy Strategy Rev.* **2025**, *59*, 101736. [\[CrossRef\]](#)
90. Eze, S.; Ijomah, W.; Wong, T.C. Accessing medical equipment in developing countries through remanufacturing. *J. Remanufacturing* **2019**, *9*, 207–233. [\[CrossRef\]](#)
91. Xu, L.; Wang, Y.; Solangi, Y.A.; Zameer, H.; Shah, S.A.A. Off-grid solar PV power generation system in Sindh, Pakistan: A techno-economic feasibility analysis. *Processes* **2019**, *7*, 308. [\[CrossRef\]](#)
92. Soto, E.A.; Hernandez-Guzman, A.; Vizcarrondo-Ortega, A.; McNealey, A.; Bosman, L.B. Solar Energy Implementation for Health-Care Facilities in Developing and Underdeveloped Countries: Overview, Opportunities, and Challenges. *Energies* **2022**, *15*, 8602. [\[CrossRef\]](#)
93. Javadi, D.; Ssempebwa, J.; Isunji, J.B.; Yevoo, L.; Amu, A.; Nabweimba, E.; Pfeiffer, M.; Agyepong, I.; Severi, L. Implementation research on sustainable electrification of rural primary care facilities in Ghana and Uganda. *Health Policy Plan.* **2020**, *35*, II124–II136. [\[CrossRef\]](#) [\[PubMed\]](#)
94. Olatomiwa, L.; Blanchard, R.; Mekhilef, S.; Akinyele, D. Hybrid renewable energy supply for rural healthcare facilities: An approach to quality healthcare delivery. *Sustain. Energy Technol. Assess.* **2018**, *30*, 121–138. [\[CrossRef\]](#)
95. Izuka, U.; Ojo, G.G.; Ayodeji, S.A.; Ndiwe, T.C.; Ehiaguina, V.E. Powering Rural Healthcare with Sustainable Energy: A Global Review of Solar Solutions. *Eng. Sci. Technol. J.* **2023**, *4*, 190–208. [\[CrossRef\]](#)
96. Khan, S.; Rashid, M.; Husain, M.A.; Rahim, A.; Shah, S.U. Potential & Current Status of Solar Energy in Pakistan Policy, Planning & Strategy. *Int. J. Eng. Work.* **2020**, *07*, 98–108. [\[CrossRef\]](#)
97. Opoku, R.; Adjei, E.A.; Obeng, G.Y.; Severi, L.; Bawa, A.-R. Electricity Access, Community Healthcare Service Delivery, and Rural Development Nexus: Analysis of 3 Solar Electrified CHPS in Off-Grid Communities in Ghana. *J. Energy* **2020**, *2020*, 9702505. [\[CrossRef\]](#)
98. Concessao, L.; Meenawat, H.; Ginoya, N.; Hazarika, M.; Gupta, D.K.; Sahay, V. A Spoonful of Solar to Help the Medicine go Down Exploring Synergies Between Health Care and Energy. *World Resour. Inst.* **2023**. [\[CrossRef\]](#)
99. McCarney, S.; Robertson, J.; Arnaud, J.; Lorensen, K.; Lloyd, J. Using solar-powered refrigeration for vaccine storage where other sources of reliable electricity are inadequate or costly. *Vaccine* **2013**, *31*, 6050–6057. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Riva, F.; Ahlborg, H.; Hartvigsson, E.; Pachauri, S.; Colombo, E. Electricity access and rural development: Review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling. *Energy Sustain. Dev.* **2018**, *43*, 203–223. [\[CrossRef\]](#)
101. López-González, A.; Domenech, B.; Ferrer-Martí, L. Sustainability evaluation of rural electrification in cuba: From fossil fuels to modular photovoltaic systems: Case studies from sancti spiritus province. *Energies* **2021**, *14*, 2480. [\[CrossRef\]](#)

102. Solar for Health | United Nations Development Programme. Available online: <https://www.undp.org/energy/our-flagship-initiatives/solar-for-health> (accessed on 8 August 2024).
103. Solar for health by United Nations Development Programme—United Nations Development Programme | UNDP—Exposure. Available online: <https://stories.undp.org/solar-for-health> (accessed on 14 May 2025).

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