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POWERING RURAL HEALTHCARE WITH SUSTAINABLE ENERGY: A GLOBAL REVIEW OF SOLAR SOLUTIONS

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ABSTRACT

Access to reliable healthcare and sustainable energy remains a global challenge, particularly in rural and underserved communities. This review paper explores the integration of solar energy solutions in rural healthcare settings, shedding light on the transformative impact of this innovative approach. This paper also explores the multifaceted benefits, challenges, and future directions of solar-powered healthcare through a comprehensive examination of the literature. Solar energy solutions in rural healthcare provide reliable power for medical equipment, extend operating hours, and improve lighting, leading to enhanced healthcare services and more accurate diagnoses. Moreover, solar-powered vaccine refrigeration ensures the potency and safety of vaccines, contributing to improved public health outcomes. Financial sustainability is bolstered as solar solutions reduce healthcare costs and offer financial independence to facilities. Environmental sustainability is achieved through reduced carbon footprints and responsible resource use. Beyond healthcare services, solar initiatives empower local communities by creating employment opportunities and enhancing resilience

in emergencies. Challenges such as initial costs, maintenance, adverse weather conditions, scalability, and policy hurdles are addressed through innovative financing models, capacity building, climate-resilient solutions, standardized monitoring systems, advocacy, and technological advancements. As the world seeks to achieve universal healthcare and sustainable development, solar-powered healthcare exemplifies the potential of renewable energy to drive positive change. This review paper emphasizes that we can improve healthcare access, quality, and sustainability by harnessing the sun's energy, ultimately illuminating the path toward brighter, healthier, and more equitable rural communities.

Keywords: Solar Energy, Rural Healthcare, Sustainable Energy, Healthcare Access, Renewable Energy, Healthcare Quality, Financial Sustainability, Environmental Sustainability, Future Directions.

INTRODUCTION

Access to quality healthcare is a fundamental human right, yet billions of people, primarily residing in remote and rural areas of the world, still struggle to obtain adequate medical services (Farmer, 2008). This healthcare divide is exacerbated by the lack of reliable and sustainable energy sources in these regions, which often hampers the functioning of healthcare facilities. The global healthcare community recognizes the urgent need to bridge this gap and make healthcare accessible to all. One promising solution emerging on the horizon is integrating solar energy systems into rural healthcare infrastructure (Charlton, 2016; Mbunge, Batani, Gaobotse, & Muchemwa, 2022). This paper embarks on a journey to explore the transformational potential of solar energy in powering rural healthcare, offering an in-depth global review of solar solutions and their implications.

Inequities in healthcare access have persisted for decades, with rural and remote communities bearing the brunt of the disparity. According to the World Health Organization (WHO), approximately half of the global population still lacks access to essential healthcare services (Development, 2010). Rural areas, where healthcare infrastructure is often underdeveloped and underfunded, face even greater challenges. The reasons behind this inequality are multifaceted, encompassing geographical isolation, limited resources, and inadequate transportation networks. However, one factor consistently stands out as a significant barrier to rural healthcare development: the absence of reliable and sustainable energy sources.

Energy poverty, the lack of access to modern energy services, affects nearly 1 billion people worldwide. This dire energy situation has dire consequences for rural healthcare facilities. In many off-grid or unreliable-grid settings, healthcare centers rely on expensive, polluting, and often insufficient energy sources, such as diesel generators or kerosene lamps (González-Eguino, 2015; Sovacool, 2012). These energy sources not only strain already limited healthcare budgets but also jeopardize patient care and safety. The erratic power supply leads to the spoilage of medicines and vaccines stored in refrigerators, limits the use of life-saving medical equipment, and hampers the efficiency of healthcare operations. The impacts of energy poverty extend beyond the clinic walls, affecting the daily lives of healthcare workers and patients alike. For example, health workers labor under inadequate lighting conditions, making diagnoses and treatments more challenging, while patients may hesitate to seek care due to the uncertainty of healthcare availability.

In recent years, solar energy has emerged as a beacon of hope in the quest to overcome the energy challenges plaguing rural healthcare. Solar solutions, encompassing photovoltaic panels, solar water heaters, and energy storage systems, offer the promise of reliable, clean, and sustainable power. These systems harness the sun's abundant energy, converting it into electricity and heat, and can be customized to suit the unique needs of healthcare facilities in rural areas. Solar energy's appeal lies in its environmental benefits and ability to deliver consistent power even in the remotest corners of the globe (Chau, Yu, Fernando, & Iu, 2017; Hasan et al., 2023). As a renewable and abundant resource, the sun can provide a lifeline to healthcare centers that have long operated in the shadows of energy scarcity. By relying on solar energy, rural healthcare facilities can enhance their capacity to deliver essential services, improve patient care, and contribute to their communities' overall health and well-being.

This paper sets out to comprehensively explore the nexus of sustainable energy and rural healthcare, with a specific focus on solar solutions. It seeks to provide a global review of the current state of solar-powered healthcare initiatives, their impacts, and the challenges encountered during their implementation. By shedding light on successful case studies, policy frameworks, and emerging trends, this review aims to inform policymakers, healthcare practitioners, and researchers about the potential of solar energy to transform rural healthcare.

This research paper aims to examine the existing literature on rural healthcare challenges, renewable energy integration, and solar solutions. It aims to present a range of case studies and examples from diverse global contexts where solar energy has been implemented in rural healthcare settings and to assess the impact of solar-powered healthcare solutions on healthcare accessibility, quality, and sustainability. It also aims to analyze the role of government policies, regulatory frameworks, and financial incentives in promoting the adoption of solar solutions in rural healthcare and to identify the challenges and future directions of solar-powered rural healthcare.

In an era where the intersection of healthcare, sustainability, and renewable energy holds immense promise, this review seeks to contribute to the discourse by illuminating the path toward healthier and more sustainable rural communities. Through a comprehensive exploration of solar solutions in rural healthcare, we endeavor to inspire action, inform policy decisions, and ultimately foster a brighter, healthier, and more equitable future for all.

LITERATURE REVIEW

Several international declarations and agreements, such as the United Nations Universal Declaration of Human Rights, recognize access to healthcare as a fundamental human right. However, despite these admirable ideals, there are still healthcare disparities around the world, with rural and remote populations frequently suffering from poor access to necessary services. This section presents a comprehensive literature review that sheds light on the challenges faced by rural healthcare and the potential of solar energy solutions to bridge the gap.

Rural Healthcare Challenges

One of the primary challenges in rural healthcare is geographical isolation. Rural communities are often located far from urban centers where healthcare facilities and specialists are concentrated (Hee & Mueller, 2022). This isolation leads to longer travel times to reach healthcare centers, making access to care more difficult, especially in emergencies. Additionally, rural areas typically have limited healthcare infrastructure, with fewer hospitals,

clinics, and healthcare professionals per capita compared to urban areas (Gaede & Versteeg, 2011; Rechel et al., 2016).

In many rural areas, inadequate transportation networks further exacerbate healthcare access issues. Poor road conditions and the lack of reliable public transportation make it challenging for residents to access healthcare services when needed. Ambulances and emergency medical services often face delays due to the difficulty of reaching remote locations. Rural communities also tend to have lower income levels, making healthcare affordability a significant concern. High out-of-pocket healthcare expenses can deter individuals from seeking necessary medical care, leading to delayed treatment and poorer health outcomes (Dumitrache, Nae, Simion, & Taloş, 2020; Sabokbar, Mohammadi, Tahmasbi, Rafii, & Hosseini, 2021).

Energy Poverty and Healthcare

Energy poverty, the lack of access to modern energy services, compounds the challenges rural healthcare facilities face. Energy poverty can take various forms, including a lack of access to electricity or reliance on polluting and expensive energy sources. According to the International Energy Agency (IEA), approximately 789 million people worldwide lacked access to electricity in 2018, with many of them residing in rural areas (Khirennas, Talha, Kaabeche, & Bakelli, 2020).

Energy poverty's impact on healthcare is profound. Healthcare facilities in rural areas often rely on fossil fuel-based generators, which are expensive to operate and maintain. These generators provide intermittent and unreliable power, compromising the operation of medical equipment, refrigeration of vaccines and medicines, and the overall quality of healthcare services. Power interruptions can lead to equipment malfunctions and treatment delays, risking patients' lives (Guruswamy, 2011; Olatomiwa et al., 2022).

Moreover, the use of kerosene lamps for lighting in healthcare settings can result in poor visibility, making diagnoses and treatments more challenging. Additionally, the indoor air pollution generated by kerosene lamps and cooking with solid fuels contributes to respiratory illnesses, further burdening the healthcare system.

Solar Energy Solutions in Healthcare

Solar energy, as a clean and renewable resource, offers a promising solution to address the energy needs of rural healthcare facilities (Shahsavari & Akbari, 2018). Solar energy is harnessed through photovoltaic (PV) panels, which convert sunlight into electricity, and solar thermal systems, which capture and store solar heat for various applications, including water heating and space heating (Ewim, Abolarin, Scott, & Anyanwu, 2023).

Solar energy solutions offer several advantages for rural healthcare settings. They can provide a stable and continuous power supply, reducing the risk of power outages and equipment failures. Once installed, solar panels require minimal maintenance, resulting in lower long-term operational costs compared to fossil fuel generators. Solar energy is a clean and environmentally friendly source of power, reducing greenhouse gas emissions and mitigating climate change. Solar systems allow healthcare facilities to become less reliant on external sources of energy, enhancing their self-sufficiency. Consistent power supply enables healthcare providers to deliver better care, reducing treatment delays and improving patient outcomes (Franco, Shaker, Kalubi, & Hostettler, 2017; Olatomiwa et al., 2022; Panwar, Kaushik, & Kothari, 2011).

Across the globe, numerous initiatives have harnessed the potential of solar energy to power rural healthcare facilities (Shaaban & Petinrin, 2014). These initiatives serve as valuable case studies for understanding the impact and challenges of solar solutions in healthcare. Based in Rajasthan, India, Barefoot College has pioneered a solar electrification model that empowers rural women to become solar engineers. This program trains women from rural areas to install, maintain, and repair solar panels. The solar-electrified villages, equipped with solar-powered healthcare centers, have seen improvements in healthcare access, as the availability of electricity enables better healthcare services (Strickland, 2016; Usman).

The We Care Solar Suitcase is a portable solar-powered unit designed to provide electricity to remote healthcare facilities with limited access to power. This suitcase contains solar panels, LED lights, a battery, and medical equipment chargers. Deployed in various African and Asian countries, this innovation has enabled healthcare workers to perform life-saving procedures even during nighttime hours. The storage of vaccines and medicines at appropriate temperatures is critical for maintaining their efficacy. Solar-powered vaccine refrigerators have been deployed in multiple countries to ensure that rural healthcare centers can safely store vaccines. These refrigerators use solar energy to maintain a consistent temperature, reducing the risk of spoiled vaccines and enabling vaccination programs in remote areas. In some African countries, solar energy has been utilized to support telemedicine initiatives. Solar-powered clinics equipped with telemedicine facilities allow remote communities to access medical consultations and specialist services through video conferencing. This approach enhances healthcare access in areas where specialist healthcare providers are scarce (J. U. Ahmed, Gazi, Iqbal, Islam, & Talukder, 2020; Basu, Banerjee, & Sweeny, 2013; Eanelli, 2019a; WHO, 2014).

The Impact of Solar Solutions on Rural Healthcare

The implementation of solar solutions in rural healthcare settings has led to notable improvements in the quality and availability of healthcare services. Consistent power supply enables healthcare facilities to effectively operate essential medical equipment, such as X-ray machines, ultrasound devices, and incubators. Moreover, well-lit healthcare facilities improve the accuracy of diagnoses and the quality of treatments. Solar-powered vaccine refrigerators ensure the safe storage of vaccines, reducing wastage and enabling effective vaccination programs. Medicines that require refrigeration, such as insulin and certain antibiotics, remain effective, leading to better healthcare outcomes (Dimitrievski et al., 2021; Olatomiwa, Blanchard, Mekhilef, & Akinyele, 2018; Olatomiwa et al., 2022).

Many rural healthcare facilities equipped with solar energy systems can extend their operating hours into the evening. This extended availability is particularly beneficial in emergencies and for accommodating patients' schedules, enhancing overall healthcare access. The shift to solar energy can reduce healthcare costs in rural areas. Solar systems have lower operational and maintenance costs compared to traditional generators, freeing up resources for improving healthcare services and infrastructure (Babatunde, Adedaja, Babatunde, & Denwigwe, 2019).

Governments play a crucial role in promoting the adoption of solar solutions in healthcare. Financial incentives, such as subsidies and tax credits for solar installations, can encourage healthcare facilities to invest in solar technology. Governments can also provide grants or low-interest loans to facilitate solar projects in underserved areas. Clear regulations and standards for solar installations ensure the safety and effectiveness of solar-powered

healthcare systems. Regulatory frameworks can streamline the approval process for solar projects and provide guidelines for their maintenance and operation (Reddy, 2015; Zalengera et al., 2020). Public-private partnerships can facilitate the implementation of solar solutions in rural healthcare. Collaborations between governments, non-governmental organizations (NGOs), and private sector entities can leverage resources and expertise to scale up solar-powered healthcare initiatives.

Challenges and Future Directions

Despite the promise of solar solutions in rural healthcare, several challenges remain. The upfront costs of solar installations can be a barrier to cash-strapped rural healthcare facilities. Access to financing and support for these initial investments is essential. Ensuring the proper maintenance and repair of solar systems requires trained personnel. Training programs for healthcare workers and technicians must be established and sustained (Weir, 2018).

Solar energy generation can be affected by weather conditions, such as cloudy days or dust accumulation on panels. Solutions to mitigate these factors need to be explored. Scaling up solar-powered healthcare initiatives to reach all underserved rural areas remains a significant challenge. Strategies for expansion and replication must be developed. Effective data collection and monitoring systems are crucial for assessing the impact of solar solutions on healthcare outcomes. These systems need to be integrated into healthcare facilities (Amankwah-Amoah, 2015; Yaacoub & Alouini, 2020).

Inconsistent policies and regulations can hinder the growth of solar-powered healthcare. Advocacy for supportive policies and regulatory harmonization is essential. Continued advancements in solar technology, energy storage, and energy management systems hold the potential to address some of the existing challenges and further improve the viability of solar-powered healthcare (Brown, Soni, Lapsa, Southworth, & Cox, 2020).

METHODOLOGY

This section outlines the research methodology employed to conduct a global review of solar solutions in rural healthcare settings. The methodology encompasses the selection of literature, data collection processes, and the criteria for the inclusion of case studies and examples.

Selection of Literature

A systematic approach to the selection of literature was followed to conduct a comprehensive review of solar solutions in rural healthcare. A thorough literature search was conducted using academic databases, scholarly journals, government reports, international organizations' publications, and grey literature. The databases and search engines utilized included but were not limited to PubMed, Google Scholar, Web of Science, and relevant government websites (e.g., US Department of Energy, World Health Organization).

The search terms used included variations and combinations of the following keywords: "solar energy," "renewable energy," "solar power," "solar solutions," "rural healthcare," "healthcare access," "energy poverty," "sustainability," "case study," "impact," and "policy."

Data Collection Processes

The data collection process involved the systematic review of selected literature and the extraction of relevant information. Data extraction was carried out using a structured template that included the following variables:

- Title and citation of the publication.

- Publication date.
- Geographic region or country of the case study.
- Description of the healthcare facility or initiative.
- Impacts on healthcare access, quality, and sustainability.
- Challenges and barriers encountered.
- Policy and regulatory framework.

Data from the selected literature were synthesized to identify common themes, trends, and key findings. The synthesis process involved categorizing information based on the objectives and research questions of the review.

Criteria for Inclusion of Case Studies and Examples

Case studies and examples from various regions were included to provide concrete and illustrative examples of solar solutions in rural healthcare. They were selected to represent different geographic regions, including but not limited to Africa, Asia, Europe, and the Americas. This approach aimed to ensure a global perspective and account for regional variations in healthcare infrastructure, energy access, and policy contexts.

A range of solar energy solutions, including solar panels, solar water heaters, and solar-powered medical equipment, were considered for inclusion to showcase the diversity of applications and technologies. Case studies and examples were prioritized based on their potential to illustrate significant impacts on healthcare access, quality, and sustainability. Initiatives demonstrating innovative approaches to addressing rural healthcare challenges through solar solutions were given special attention. They were selected to reflect different policy and regulatory frameworks, highlighting the role of government support and incentives in promoting solar-powered healthcare solutions.

Limitations

While every effort was made to conduct a comprehensive and systematic review, certain limitations should be acknowledged. The review is subject to the availability of relevant literature in the selected databases and sources. Some relevant projects and initiatives may not have been documented or published. The exclusion of non-English publications may result in a language bias, potentially omitting valuable case studies and examples from non-English-speaking regions. The review may be subject to publication bias, as successful or well-documented projects are more likely to be published and accessible.

Solar Energy Solutions in Rural Healthcare

The integration of solar energy solutions in rural healthcare infrastructure has emerged as a transformative approach to addressing the energy and healthcare disparities faced by remote and underserved communities worldwide. Solar solutions, encompassing PV panels, solar water heaters, and energy storage systems, promise to provide reliable, clean, and sustainable power to rural healthcare facilities. This section delves into the multifaceted aspects of solar energy solutions in rural healthcare, elucidating their benefits, innovative applications, and tangible impacts on healthcare access, quality, and sustainability.

Harnessing Solar Energy for Rural Healthcare

Solar energy harnesses the abundant and renewable power of the sun to generate electricity and heat, offering a viable solution to the energy challenges confronting rural healthcare facilities. By converting sunlight into electricity through photovoltaic panels and capturing

solar heat for water heating and space heating, solar energy systems provide a reliable and sustainable source of power for essential healthcare functions.

Photovoltaic panels, commonly known as solar panels, are a cornerstone of solar energy solutions. These panels consist of solar cells that convert sunlight into direct current (DC) electricity. In rural healthcare settings, PV panels are typically installed on the rooftops of healthcare facilities or in nearby solar arrays to maximize sunlight exposure (Delfanti, Falabretti, & Merlo, 2015). Solar water heaters utilize solar collectors to capture solar heat and transfer it to water, providing a cost-effective solution for hot water production in healthcare facilities (S. F. Ahmed et al., 2021). These systems are particularly valuable for tasks such as sterilization, laundry, and bathing in healthcare settings.

Energy storage systems, often integrated with PV panels, store excess solar-generated electricity in batteries for use during cloudy periods or at night. These systems enhance the reliability of power supply, ensuring uninterrupted healthcare operations (Qadrdan, Jenkins, & Wu, 2018).

Benefits of Solar Energy Solutions

The adoption of solar energy solutions in rural healthcare settings offers many benefits beyond energy provision. These benefits address critical challenges faced by healthcare facilities in remote areas. One of the most significant advantages of solar energy solutions is their reliability. Solar panels provide a consistent and stable power supply, reducing the risk of power outages caused by grid failures or generator malfunctions. This reliability is paramount for healthcare facilities where continuous power is essential for patient care and the operation of medical equipment.

Solar energy systems, once installed, have relatively low operational and maintenance costs compared to traditional fossil fuel generators. Reducing fuel expenses and maintenance requirements frees up financial resources that healthcare facilities can allocate toward improving patient care, staff training, or infrastructure development (Mendonça, 2012). The environmental sustainability of solar energy solutions aligns with global efforts to reduce greenhouse gas emissions and combat climate change. Solar panels produce electricity without emitting harmful pollutants, contributing to cleaner air and reduced carbon footprint.

Solar energy solutions empower healthcare facilities to become less reliant on external sources of energy, enhancing their energy independence. This self-sufficiency reduces vulnerability to energy supply disruptions and price fluctuations associated with conventional energy sources. The consistent power supply enabled by solar energy solutions directly impacts healthcare outcomes. Medical equipment, such as diagnostic devices, incubators, and surgical instruments, operates optimally with uninterrupted power (Mekhilef, Saidur, & Safari, 2011). This leads to more accurate diagnoses and treatments, ultimately improving patient health outcomes.

Solar-Powered Healthcare Initiatives

Solar-powered healthcare initiatives have been implemented in various rural and remote regions across the globe. These initiatives serve as tangible examples of the transformative potential of solar energy in healthcare delivery. Below are selected case studies and examples that illustrate the diverse applications and impact of solar solutions in rural healthcare:

Barefoot College's Solar Electrification Model (India)

Based in Rajasthan, India, Barefoot College has pioneered a solar electrification model that empowers rural women to become solar engineers. Through a unique training program, women from rural areas are equipped with the skills to install, maintain, and repair solar panels. These solar-electrified villages have improved healthcare access, as solar power enables better healthcare services, including lighting, refrigeration for vaccines, and medical equipment operation. The success of this model demonstrates the transformative potential of local empowerment and sustainable energy in rural healthcare (Chakrabarty, 2023; Roy, 2012).

We Care Solar Suitcase (Global)

The "We Care Solar Suitcase" is a portable, solar-powered unit designed to provide electricity to remote healthcare facilities with limited access to power. Equipped with solar panels, LED lights, a battery, and medical equipment chargers, this innovation has been deployed in various African and Asian countries. The suitcase ensures that healthcare workers can perform life-saving procedures even during nighttime hours, addressing one of the critical challenges of rural healthcare access. It represents a scalable and adaptable solution to improving healthcare services in off-grid areas (Eanelli, 2019a).

Solar-Powered Vaccine Refrigerators (Various Locations)

Solar-powered vaccine refrigerators have been deployed in numerous countries to ensure the safe storage of vaccines. These refrigerators use solar energy to maintain a consistent temperature, reducing the risk of spoiled vaccines. Solar-powered refrigeration is essential for effective vaccination programs in regions with unreliable electricity grids or no access to electricity, such as parts of sub-Saharan Africa. The reliability of vaccine storage contributes to improved public health outcomes, particularly in the prevention of vaccine-preventable diseases.

Solar-Powered Telemedicine (Africa)

In some African countries, solar energy has been leveraged to support telemedicine initiatives in rural areas (Ihuoma, 2011). Solar-powered clinics equipped with telemedicine facilities allow remote communities to access medical consultations and specialist services through video conferencing. This approach extends healthcare access to underserved populations and demonstrates the synergy between renewable energy and healthcare technology (Faruk et al., 2017).

Impact on Rural Healthcare

The integration of solar energy solutions in rural healthcare has resulted in tangible impacts that extend across healthcare access, quality, and sustainability. Solar energy solutions enable healthcare facilities to operate essential medical equipment reliably. This includes diagnostic equipment like X-ray machines and ultrasound devices, which are crucial for accurate diagnoses and treatment planning. Additionally, well-lit healthcare facilities improve visibility and comfort for healthcare workers and patients alike, enhancing the quality of care.

Solar-powered vaccine refrigerators ensure the safe storage of vaccines, reducing wastage and enabling effective vaccination programs. Medicines that require refrigeration, such as insulin and certain antibiotics, remain effective, leading to better healthcare outcomes. Many rural healthcare facilities equipped with solar energy systems can extend their operating hours into the evening. This extended availability is particularly beneficial in emergencies and for

accommodating patients' schedules, enhancing overall healthcare access. The shift to solar energy can reduce healthcare costs in rural areas. Solar systems have lower operational and maintenance costs compared to traditional generators, freeing up resources for improving healthcare services and infrastructure.

Policy and Regulatory Frameworks

Government support plays a pivotal role in promoting solar solutions in healthcare facilities. Governments can offer financial incentives, such as subsidies, grants, and tax credits, to healthcare facilities that invest in solar energy systems. These incentives help offset the initial installation costs, making solar solutions more accessible to rural healthcare institutions. Providing healthcare facilities with access to low-interest loans for solar installations encourages investment in renewable energy. This financial support helps facilities overcome the financial barrier associated with upfront costs.

Governments can fund research and development projects focused on innovative solar applications in healthcare. This support fosters technological advancements and the discovery of new ways to improve healthcare services through solar energy. Governments can facilitate training programs for healthcare staff and technicians on installing, maintaining, and operating solar energy systems. By enhancing local expertise, these programs ensure the long-term sustainability of solar-powered healthcare facilities.

Clear regulations and standards are essential for successfully integrating solar energy solutions in healthcare settings (Dincer, 2000). Regulations should stipulate safety standards for installing and maintaining solar panels and associated equipment. Ensuring the safety of healthcare workers and patients is paramount. Governments need to establish policies and guidelines for grid connection in cases where healthcare facilities are connected to the grid. This includes mechanisms for net metering, which allows healthcare facilities to sell excess solar-generated electricity back to the grid (Javadi et al., 2020).

Regulations should encourage the use of environmentally friendly solar technologies and disposal practices for end-of-life solar components to minimize environmental impacts. Accreditation processes for solar installers and technicians can help maintain high-quality standards in installing and maintaining solar energy systems. Public-private partnerships (PPPs) can be pivotal in scaling up solar-powered healthcare initiatives. Collaborations between governments, non-governmental organizations (NGOs), and private sector entities leverage resources and expertise. These partnerships facilitate the implementation of solar projects, access to funding, and sharing best practices (Agbo, 2014; Fife & Hosman, 2007; Newcombe & Ackom, 2017).

In summary, integrating solar energy solutions in rural healthcare is a compelling illustration of how renewable energy can be harnessed to address pressing global challenges. Solar solutions enhance healthcare access, quality, and sustainability in remote and underserved communities by providing reliable and sustainable power. The successful implementation of solar-powered healthcare initiatives, exemplified by case studies and examples from diverse regions, underscores the transformative potential of renewable energy in healthcare delivery. Governments and stakeholders must continue supporting solar-powered healthcare expansion through financial incentives, clear regulations, and public-private partnerships. Addressing challenges related to initial costs, maintenance, scalability, and policy hurdles is crucial to ensuring the widespread adoption of solar solutions. Furthermore, ongoing technological

advancements promise to make solar energy even more accessible and efficient in rural healthcare settings.

In an era where healthcare access and sustainability are global priorities, the fusion of solar energy and healthcare exemplifies the innovative solutions that can drive positive change and empower communities to lead healthier lives. As the world seeks to build back better and achieve universal healthcare, solar energy is a beacon of hope, lighting the way toward brighter, healthier, and more equitable rural communities.

Impact on Rural Healthcare

Integrating solar energy solutions into rural healthcare settings has ushered in a new healthcare access, quality, and sustainability era in remote and underserved communities. This section explores the multifaceted impact of solar energy solutions on rural healthcare, shedding light on how these technologies have improved healthcare services, public health outcomes, and the overall well-being of communities in need.

Enhanced Healthcare Services

One of the most immediate and profound impacts of solar energy solutions in rural healthcare is the provision of reliable power for essential medical equipment. Solar panels, combined with energy storage systems, ensure a continuous supply of electricity, reducing the risk of power outages that could jeopardize patient care. Medical equipment such as X-ray machines, ultrasound devices, and laboratory equipment can function optimally with uninterrupted power. This enhances the diagnostic capabilities of rural healthcare facilities, allowing for more accurate assessments and treatment plans.

The consistent power supply enabled by solar energy solutions also extends the operating hours of rural healthcare facilities. Many of these facilities, previously constrained by limited access to electricity or unreliable grid power, can now offer healthcare services in the evening and at night. This extended availability is particularly beneficial in emergencies and for accommodating patients' schedules, ultimately leading to improved healthcare access (Pearce, 2009; Shaqsi, Sopian, & Al-Hinai, 2020).

Well-lit healthcare facilities contribute to a more comfortable and welcoming environment for both healthcare workers and patients. Solar-powered lighting systems enhance visibility and safety, especially in areas where electrical lighting is scarce. Proper lighting is critical for performing medical procedures, conducting examinations, and ensuring patients' overall well-being. The improved physical infrastructure and comfort of healthcare facilities positively impact the quality of care provided.

Increased Vaccine and Medicine Reliability

Solar-powered vaccine refrigeration systems play a vital role in maintaining the potency and safety of vaccines in rural healthcare settings. These refrigerators use solar energy to maintain a consistent temperature, ensuring that vaccines remain effective. In regions with unreliable electricity grids or no electricity access, solar-powered vaccine refrigeration is essential for the success of vaccination programs. The reliability of vaccine storage reduces vaccine wastage and contributes to improved public health outcomes, particularly in the prevention of vaccine-preventable diseases.

Beyond vaccines, solar energy solutions also impact the storage of medicines that require refrigeration. Insulin, certain antibiotics, and other medications that are sensitive to temperature fluctuations can be safely stored in solar-powered refrigerators. This ensures that

essential medicines remain effective and readily available to patients, enhancing healthcare quality and effectiveness (Nadimuthu & Victor, 2022).

Cost Reduction and Financial Sustainability

Transitioning to solar energy in rural healthcare settings results in cost savings that can be redirected toward improving healthcare services. Solar energy systems have lower operational and maintenance costs compared to traditional fossil fuel generators. Eliminating fuel expenses, reducing maintenance requirements and extending equipment lifespan contribute to financial sustainability. Healthcare facilities can allocate these saved resources to staff training, medical supplies, infrastructure development, and other critical needs.

Solar energy solutions also offer rural healthcare facilities a degree of financial independence. By generating their own electricity, healthcare institutions become less reliant on external sources of energy, mitigating the financial risk associated with energy price fluctuations and supply disruptions. This financial stability allows healthcare facilities to plan and invest in the long-term well-being of their communities (Fragkos et al., 2021).

Environmental Sustainability

The adoption of solar energy solutions in rural healthcare settings aligns with global efforts to reduce greenhouse gas emissions and combat climate change. Solar panels produce electricity without emitting harmful pollutants, contributing to cleaner air and a reduced carbon footprint. In rural areas where healthcare access is often intertwined with environmental health, reducing local pollution from traditional energy sources can lead to direct health benefits for communities.

Solar energy solutions offer a path to sustainable energy for generations to come. The environmental benefits extend beyond reduced emissions to the preservation of natural resources. In rural areas, where healthcare facilities may be located near sensitive ecosystems or rely on natural resources for their communities' health, the shift to solar energy aligns with the principles of ecological sustainability (Olatomiwa et al., 2022).

Improved Health Outcomes

The availability of reliable power through solar energy solutions enhances healthcare providers' ability to diagnose and treat patients effectively. Modern medical equipment, such as X-ray machines, CT scanners, and laboratory analyzers, depends on a consistent power supply to function accurately. Solar-powered facilities can provide these diagnostic services consistently, leading to earlier and more precise diagnoses.

Rural healthcare facilities often serve as primary centers for maternal and child healthcare. Solar energy solutions enable these facilities to provide better care during childbirth and for newborns. The reliability of power ensures that medical equipment, including infant warmers and incubators, can operate without interruption. This contributes to reducing maternal and neonatal mortality rates, improving overall health outcomes in rural communities. Solar-powered healthcare facilities are well-suited for telemedicine initiatives, allowing remote communities to access medical consultations and specialist services through video conferencing. Patients in rural areas can receive expert medical advice without the need for time-consuming and expensive travel to distant healthcare centers. This approach extends healthcare access to underserved populations and demonstrates the synergy between renewable energy and healthcare technology (Babatunde et al., 2019; Eanelli, 2019b; Olatomiwa et al., 2022).

Community Empowerment and Resilience

Installing and maintaining solar energy systems in rural healthcare facilities often require local expertise. Solar engineers and technicians are trained to install and service solar panels and associated equipment. By providing employment opportunities for community members, solar initiatives contribute to local economic development and empower residents with valuable skills. Solar-powered healthcare facilities enhance community resilience in the face of emergencies (Bugaje, 2006). These facilities can continue to provide vital healthcare services during natural disasters or grid failures. Solar panels and energy storage systems ensure uninterrupted power supply for critical medical equipment and lighting, contributing to disaster preparedness and response efforts.

Challenges and Future Directions

The integration of solar energy solutions into rural healthcare represents a promising avenue for addressing energy and healthcare disparities. However, several challenges persist, and future directions must be carefully considered to ensure the sustainability and continued growth of solar-powered healthcare initiatives.

Challenges

The upfront costs of installing solar energy systems in rural healthcare facilities can be a significant barrier, particularly in resource-constrained settings. Many healthcare facilities in remote areas operate on tight budgets and may struggle to secure the necessary funding for solar installations. Overcoming this challenge requires innovative financing mechanisms, grants, and partnerships with governments, donors, and non-governmental organizations (NGOs) to make solar solutions financially accessible to more healthcare facilities.

The proper maintenance and operation of solar energy systems require trained personnel. Rural healthcare workers and technicians may lack the necessary skills and knowledge to maintain and repair solar panels and associated equipment. Implementing training programs is essential for building local capacity and ensuring the long-term sustainability of solar-powered healthcare facilities. These programs should focus on system maintenance, troubleshooting, and safety procedures (Ganguly, 2021).

Solar energy generation can be affected by adverse weather conditions, such as cloudy days or dust accumulation on solar panels (Ghazi & Ip, 2014). In regions prone to extreme weather events, such as hurricanes or monsoons, solar installations may be at risk of damage. Strategies to mitigate the impact of adverse weather and environmental factors on energy production should be explored. This may include the use of backup power sources, advanced cleaning methods, and robust system design to withstand harsh conditions.

Scaling up solar-powered healthcare initiatives to reach all underserved rural areas remains a significant challenge. Different regions have unique needs and contexts, so developing tailored approaches for each setting is necessary. Strategies for expansion and replication should consider factors such as local infrastructure, healthcare demand, and community engagement. Collaboration among governments, NGOs, and the private sector is crucial for achieving scalability while maintaining effectiveness.

Effective data collection and monitoring systems are crucial for assessing the impact of solar solutions on healthcare outcomes. These systems need to be integrated into healthcare facilities to track energy production, consumption, and healthcare indicators effectively. However, implementing and maintaining such systems can be challenging in resource-

constrained settings. Overcoming this challenge requires investment in technology infrastructure and training for healthcare personnel.

Future Directions

Future directions should focus on developing innovative financing models to address the challenge of initial costs. Governments, international organizations, and private sector entities can collaborate to create financing mechanisms that offer low-interest loans, grants, and subsidies for solar installations in rural healthcare facilities. Pay-as-you-go models, where healthcare facilities pay for solar energy services over time, can also be explored to make solar solutions financially accessible.

Building local capacity is essential for the long-term sustainability of solar-powered healthcare initiatives. Future directions should prioritize developing and expanding training programs for healthcare workers and technicians. These programs should cover system installation, maintenance, repair, and safety procedures. Empowering local communities with the knowledge and skills to manage solar systems will ensure the continued operation of healthcare facilities.

In regions prone to extreme weather events, developing and deploying climate-resilient solar solutions should be a priority. Solar installations should be designed to withstand severe weather conditions, such as hurricanes, floods, and extreme temperatures. Backup power sources, such as hybrid solar-diesel systems or energy storage, can provide additional resilience during extended periods of adverse weather. The development of standardized monitoring systems is crucial for evaluating the impact of solar solutions on healthcare outcomes. Future directions should focus on the creation of easy-to-implement data collection and monitoring systems that can be deployed in diverse rural healthcare settings. These systems should provide real-time data on energy production, consumption, and healthcare indicators, enabling healthcare facilities to assess their performance and make data-driven improvements.

Advocacy efforts for supportive policies and regulatory reform should continue to be a priority. Stakeholders, including governments, NGOs, and healthcare associations, should work together to advocate for clear and consistent regulations related to solar installations in healthcare facilities. Policy reforms should address permit requirements, grid connection policies, and tax incentives to create an enabling environment for solar-powered healthcare initiatives. Investment in research and development (R&D) is essential to drive innovation in solar technology tailored to rural healthcare needs. Future R&D efforts should focus on improving solar panel efficiency, energy storage systems, and energy management technology. Innovation in these areas can lead to more cost-effective and reliable solar solutions, further enhancing their viability in rural healthcare settings.

To conclude, the challenges and future directions outlined in this section highlight the importance of ongoing efforts to harness the full potential of solar energy in rural healthcare. Overcoming challenges related to initial costs, maintenance, adverse weather conditions, scalability, data monitoring, policy reform, and technology innovation requires coordinated action and commitment from multiple stakeholders. As the world seeks to build back better and achieve universal healthcare, the fusion of solar energy and healthcare exemplifies the innovative solutions that can drive positive change and empower communities to lead healthier lives.

CONCLUSION

The fusion of solar energy solutions with rural healthcare has emerged as a transformative force, addressing critical energy and healthcare disparities in remote and underserved communities worldwide. This review paper, drawing from extensive literature analysis and a comprehensive exploration of solar-powered healthcare initiatives, underscores this innovative approach's profound impact, benefits, challenges, and future directions. Solar energy integration has revolutionized healthcare access, quality, and sustainability in rural areas. These solutions enhance healthcare services by providing reliable power for essential medical equipment, extending operating hours, and improving lighting in healthcare facilities. The result is more accurate diagnosis, improved patient care, and increased healthcare access, especially during emergencies and maternal and child healthcare. Moreover, solar-powered healthcare has strengthened vaccine storage, reduced costs, fostered economic development, and enhanced community resilience in the face of disasters, making it a beacon of hope for brighter, healthier, and more equitable rural communities.

However, this promising approach faces challenges, including installation costs, maintenance, scalability, adverse weather, and policy hurdles. Addressing these challenges is crucial for long-term sustainability. The future of solar-powered healthcare lies in innovative financing, community empowerment, climate-resilient solutions, monitoring systems, policy support, and technological advancements. Solar-powered healthcare remains a testament to renewable energy's potential for positive change as the world pursues universal healthcare and sustainable development. By tackling challenges and embracing future opportunities, stakeholders can ensure that solar-powered healthcare initiatives continue illuminating the path toward accessible, sustainable healthcare powered by the sun.

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