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Research Article

Performance evaluation of off-grid solar systems for critical medical instruments in remote regions

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Abstract In areas with limited access to electricity or during power outages, ensuring continuous and reliable use of grid-powered electrical instruments is challenging, especially in remote emergency centers. A stable source of electricity is crucial to prevent disruptions in power supply, as they can lead to severe medical complications, jeopardize patient well-being, and even result in fatal incidents. To address this issue, integrating renewable electricity sources such as off-grid solar systems into existing power supply infrastructure can be a viable solution. Recent studies suggest that off-grid solar systems can be reliable and sustainable options for powering medical facilities, particularly in areas lacking uninterrupted grid connectivity. Therefore, this research aims to evaluate the feasibility, benefits, and challenges of integrating off-grid power to support critical medical instruments. Based on an extensive literature review, interviews with experts, and surveys among relevant users, this study finds that the system has the capability to maintain a consistent, dependable power supply, even during adverse weather conditions. Cost and feasibility are highlighted as paramount considerations, based on surveys and focus group results. The study concludes that off-grid solar systems offer an economical, low-maintenance, and environmentally sustainable alternative for remote medical facilities. Finally, this study proposes recommendations to optimize critical device performance during power outages and improve overall system functionality and efficiency.

Keywords: Off-grid solar systems, Renewable energy, Remote areas, Critical medical equipment, Photovoltaics



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1. Introduction

Continuous access to electricity is critical for essential medical instruments in healthcare facilities, including ventilators, oxygen concentrators, and defibrillators, which play a vital role in saving lives. These instruments rely on a consistent power supply to function effectively and deliver accurate results. Interruptions in electricity can have severe consequences, potentially harming patients and causing critical delays in medical procedures. Ensuring a continuous and reliable power source is crucial to maintaining the functionality of these instruments, especially in remote areas with limited grid connectivity. Renewable energy technologies, such as off-grid solar systems, provide potentially sustainable and dependable solutions for operating critical medical instruments, prioritizing patient well-being, even in challenging environments.

Renewable energy has gained popularity due to its clean and natural sources, making it environmentally friendly compared to fossil fuels. These sources are considered infinite and produce no harm to the environment, offering cost-effectiveness and emitting no harmful greenhouse emissions. Solar systems, utilizing solar panels to generate electricity from sunlight, particularly Off-Grid Photovoltaics (PV), present a practical application in areas lacking reliable grid power supply. These systems store solar-generated power in batteries for later use and convert it into the required electricity type using an inverter (Burns *et al.* 2012). Unlike diesel generators, off-grid solar systems are self-sufficient, clean, and sustainable energy sources, producing no harmful emissions and potentially being more cost-effective in the long run due to their independence from constant fuel supply (Baurzhan *et al.* 2016).

These systems show significant potential as energy sources for healthcare facilities in rural zones, ensuring a continuous and steady energy supply for critical medical equipment. When combined with grid-connected systems during the daytime, off-grid solar systems can effectively reduce energy demands in hospitals. They prove valuable, particularly in developing countries with unreliable electricity, enhancing patient health outcomes and saving lives. Proper performance evaluations are crucial to ensure the dependability and effectiveness of off-grid solar systems. Applying project management principles to these evaluations helps ensure organized and efficient processes, with monitoring and control playing crucial roles in optimizing system operations, identifying potential issues, and enhancing performance and profitability (Dauenhauer *et al.* 2020). Therefore, this study focuses on evaluating the performance of off-grid solar systems for critical medical instruments in remote and rural areas. The aim is to enhance essential healthcare outcomes, preserve non-renewable resources, and safeguard the environment. The objectives include assessing feasibility, addressing environmental and social challenges, exploring advantages over other power sources, reducing implementation costs and time, and implementing error-reduction measures. By evaluating key performance indicators and costs, ensuring workforce

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efficiency, and extending the reach to developing nations, this study aims to enhance the availability and functionality of critical medical instruments in underserved areas.

The study follows a structured approach, beginning with a comprehensive literature review, analyzing academic research on off-grid solar systems and their application in medical facilities. The methodology section outlines the research's purpose, methods, data analysis, and discussions. The results and discussion section presents the findings of the survey and their comparison with relevant literature. Based on the analysis, the study provides recommendations for engineering managers on the suitability of off-grid solar panels for powering critical medical instruments and identifies potential challenges. A concise conclusion summarizes the significant findings and links them to the project objectives, acknowledging any limitations and suggesting future research directions.

2. Literature Review

To ensure uninterrupted and efficient healthcare services in remote regions, it is essential to evaluate the performance of off-grid solar systems designed specifically for critical medical instrument applications. Limited research has been conducted in this area, and this section aims to provide a comprehensive examination of existing literature on the performance evaluation of off-grid solar systems tailored for medical instrument applications (Baurzhan *et al.* 2016).

2.1 Off-grid solar system

Solar power is recognised as a promising solution to global energy challenges, although its current contribution to the global power supply remains relatively low due to the high costs of photovoltaic (PV) panels. Studies comparing grid-connected, and off-grid solar PV installations highlight their effectiveness, dependability, and cost-effectiveness, aiding policymakers and decision-makers in tailored decision-making. Off-grid solar systems provide a decentralized and reliable source of electricity, especially in underserved regions where grid access is limited or non-existent. These systems operate independently from the main electrical grid, utilizing solar panels to generate electricity that is stored in batteries for use when sunlight is not available. Solar energy offers benefits such as income generation and improved living standards, particularly in off-grid communities in less developed remote nations. Despite challenges like high initial costs and storage expenses, ongoing advancements in technology are making solar power increasingly affordable and practical for both homes and businesses. Additionally, solar energy's sustainability and lack of adverse side effects make it an attractive alternative for those concerned about environmental impact. Leveraging renewable energy sources and adopting localised solutions can expand access to electricity, promote sustainable development, and eradicate energy poverty worldwide. Overall, solar energy proves to be a viable and practical solution for meeting the growing energy needs of remote areas while contributing to a more sustainable future (Mohtasham 2015).

2.2 Off-grid solar systems for healthcare centers

Off-grid solar power systems offer a sustainable and cost-effective solution for powering critical medical instruments in resource-limited settings, thereby improving healthcare outcomes, reducing costs, and enhancing access to quality services in health clinics facing challenges due to unreliable or inadequate electricity supply.

Two case studies conducted by Lunze & Hamer (2018) investigated the implementation of off-grid solar systems in healthcare settings. Lunze & Hamer's study focused on health clinics in southern Malawi and demonstrated the success of these solar systems in meeting the clinics' energy needs, including powering medical equipment, lighting, and refrigeration. The use of off-grid solar systems resulted in cost savings and reduced carbon emissions by reducing reliance on diesel generators. These studies emphasized the importance of involving local communities and stakeholders in the design and implementation of these systems for long-term sustainability. On the other hand, the research explored the feasibility of using off-grid solar systems to power critical medical devices in rural health centers in Uganda. Their findings indicated that solar systems could supply sufficient power to medical devices, and the initial investment could be recovered in five to seven years due to savings on fuel and maintenance costs. Both studies demonstrated the potential of off-grid solar power in healthcare facilities, providing reliable and sustainable energy solutions in remote settings (Lunze *et al.* 2019).

Worku *et al.* (2021) described the implementation of a solar-powered off-grid medical clinic in rural Ethiopia, addressing challenges stemming from unreliable electricity supply. They highlighted the reliability, cost savings, and environmental sustainability of off-grid solar power systems compared to traditional diesel generators, emphasizing their noiseless operation, minimal maintenance requirements, and absence of fuel costs. Similarly, Lazardis *et al.* (2019) developed a solar-powered water pumping and purification system for rural health centers in Ethiopia, aiming to alleviate water supply issues and reduce reliance on fossil fuels. This system effectively reduced water-borne diseases while contributing to ecological sustainability. This study conducted a systematic review, confirming the benefits of off-grid solar systems in improving electricity access, reliability, and cost-effectiveness in healthcare settings, despite challenges related to installation costs and maintenance. Additionally, Ouedraogo *et al.* (2022) evaluated an off-grid solar system in a hospital in Burkina Faso, demonstrating its reliability and cost-saving potential compared to diesel generators (Worku *et al.* 2021, Lazardis *et al.* 2019, Oueradogo *et al.* 2022).

Moreover, Yadav *et al.* (2019) demonstrated the feasibility and reliability of off-grid solar systems in a distant Indian village. Their study showed that a 1kW solar power system connected to a battery bank successfully powered medical devices, with an estimated payback period of five years and a Return on Investment (ROI) of approximately 20% (Yadav *et al.* 2019).

Collectively, the outcomes of reviewed studies underscore the promising potential of off-grid solar power systems in addressing energy challenges in healthcare settings. Case studies in Malawi and Uganda demonstrated their effectiveness in meeting energy needs and powering medical devices. Implementation of solar-powered clinics in rural Ethiopia showcased their reliability, cost-effectiveness, and environmental benefits compared to traditional diesel generators. Additionally, solar-powered water systems in Ethiopia aimed to mitigate water supply challenges and reduce reliance on fossil fuels, thus alleviating water-borne diseases. Systematic reviews provided insights into improved access to electricity and reduced energy costs in healthcare facilities. Evaluations

in Burkina Faso and India further supported the reliability and cost-saving potential of off-grid solar systems. Overall, these findings highlight the promising role of off-grid solar power in enhancing healthcare delivery, advocating for collaboration, community engagement, and continued research to ensure successful implementation and long-term sustainability.

Implementing off-grid solar power systems in healthcare facilities can significantly improve access to quality healthcare services, diminish operating expenses, and contribute to a more sustainable future (Ouedraogo *et al.* 2022). These systems present a sustainable and cost-effective solution for powering critical medical instruments in resource-limited settings, demonstrating their potential to improve healthcare outcomes, reduce costs, and enhance access to quality healthcare services. Collaboration between stakeholders, community engagement, and ongoing research is essential for their successful implementation and long-term viability. Policymakers, healthcare providers, and technology developers can benefit from the insights provided by these studies to drive positive change in healthcare delivery in resource-limited settings. Further research and implementation efforts are needed to optimise the design and effectiveness of off-grid solar systems for healthcare applications.

2.3 Challenges of off-grid solar systems in rural healthcare settings

Recent studies have investigated the use of off-grid solar systems in rural health facilities, highlighting their potential to provide reliable power for medical devices. However, challenges related to maintenance and capacity building have been identified as significant barriers to their effective implementation.

Salaam (2023) studied the use of solar-powered systems in rural health facilities in Tanzania. While providing reliable power for medical devices, these systems faced a significant challenge identified in the study such as poor maintenance. Factors such as a lack of technical knowledge, inadequate maintenance funding, and limited spare parts availability contributed to frequent breakdowns. Battery failure was the most common cause of system breakdowns, attributed to the use of low-quality batteries and over-discharging. The study recommended adequate system maintenance and repair training for health facility staff (Salaam *et al.* 2023).

Gebreslassie *et al.* (2022) also assessed the reliability of off-grid solar systems in providing electricity to health centers in rural Ethiopia. The study found that solar systems could offer reliable and sustainable power to medical devices; however, their reliability was affected by weather conditions and poor maintenance. Proper training and capacity building for local staff ensured optimal system maintenance. The study also recommended incorporating backup systems or battery storage to mitigate the impact of intermittent power supply (Gebreslassie *et al.* 2022).

In conclusion, both studies emphasize the importance of maintenance and capacity building for effectively implementing off-grid solar systems in rural health facilities (Salaam, 2023; Gebreslassie *et al.*, 2022). Poor maintenance, often due to a lack of technical knowledge and funding, leads to frequent breakdowns and affects the delivery of medical services. Proper training programs and adequate resources for maintenance are vital to ensure solar systems' reliable and sustainable functioning (Salaam *et al.* 2023, Gebreslassie *et al.* 2022). Policymakers and stakeholders in the healthcare sector are encouraged to prioritize the maintenance and sustainability of these systems to guarantee the provision of quality healthcare services in rural areas

2.4 Literature review outcomes

The literature review examined various strategies for ensuring a reliable power supply for medical instruments in remote areas, focusing particularly on renewable energy sources like solar power and battery storage systems. Solar power emerged as a promising solution due to its abundance in remote regions, low maintenance requirements, and environmental sustainability. Studies showcased the feasibility of solar-powered systems in providing continuous energy for essential medical equipment, supporting diagnosis, treatment, and patient care in remote healthcare settings. Additionally, solar power was found to align with global sustainable development goals and efforts to mitigate climate change. However, the review also identified challenges such as maintenance, technical knowledge gaps, and funding limitations that hinder the effective implementation of solar-powered systems in rural healthcare settings. Recommendations included the importance of adhering to international standards and guidelines, implementing proper training programs, and securing adequate maintenance funding to ensure the reliable and sustainable functioning of off-grid solar systems. Overall, the literature review provided valuable insights for healthcare practitioners, policymakers, and stakeholders, emphasizing the potential of solar power to improve patient care through reliable and sustainable energy access in rural zones. Further research is recommended to explore practical applications and optimize the utilization of off-grid solar systems for critical medical instruments in remote healthcare facilities.

3. Methodology

The research methodology employed in this study focused on analyzing the feasibility and effectiveness of off-grid solar systems for powering critical medical instruments in remote and underprivileged areas. The review was divided into three main components, addressing the selection of off-grid solar panels, evaluating their usage in powering medical devices, and assessing the overall effectiveness of the systems. Feasibility, reliability, safety, and cost-effectiveness were key factors considered during the rigorous evaluation processes. The data collection involved a comprehensive review of literature from reputable sources like Google Scholar and the Institute of Electrical and Electronics Engineers (IEEE), identifying gaps in existing research and providing an overview of current scholarly discourse on the topic.

The study further utilized market data and expert consultations to establish appropriate evaluation criteria. Data collection was carried out through various methods, including questionnaires, interviews, and observations. A large group of individuals, experts with extensive experience in off-grid solar panels, participated in the study. The survey, distributed through emails and online platforms, gathered insights from a diverse group, including medical professionals, energy experts, and solar energy field engineers and managers.

The comprehensive data analysis involved a meticulous examination of survey responses, which were presented in visually appealing graphs created using Excel. This approach facilitated a deeper understanding of the survey results, allowing for effective

communication of the findings. Overall, the survey results indicated a positive attitude towards the adoption of off-grid solar systems for medical instruments, emphasizing the benefits of renewable energy sources, reduced reliance on fossil fuels, and lower environmental impact.

In conclusion, the research findings strongly support the use of off-grid solar systems for powering critical medical instruments in remote or isolated areas. The study demonstrates the feasibility, reliability, and cost-effectiveness of these systems, highlighting their potential to address healthcare challenges in underserved regions. The results emphasize the positive impact of off-grid solar systems in reducing reliance on traditional systems and their suitability for emergency scenarios. These findings present compelling evidence for the adoption of off-grid solar systems in remote healthcare settings, improving access to reliable power and enhancing healthcare delivery in underserved communities.

4. Results Analysis and Discussions

4.1 Off-grid solar system

This section provides an overview of the research methodology, detailing the approach to data collection and analysis, along with supporting evidence that validates the significance of the chosen methodology. Figure 1 illustrates the key criteria to be considered when evaluating off-grid solar power for critical medical equipment. Surveyed engineers and managers, both in developed and developing countries, have expressed a preference for off-grid solutions, primarily due to the reliability of solar energy sources, which offer consistent power supply. Additionally, the capacity of energy that storage batteries can store emerges as a crucial consideration, with 67% of engineers and 83% of managers emphasizing the importance of cost-effectiveness. This suggests that participants regard the quantity of energy produced by solar panels as cost-effective for the overall system. Lastly, while approximately half of the experts considered the availability of renewable energy sources in the specific area based on weather conditions or energy demands, it is noted that this factor has less influence on decision-making.

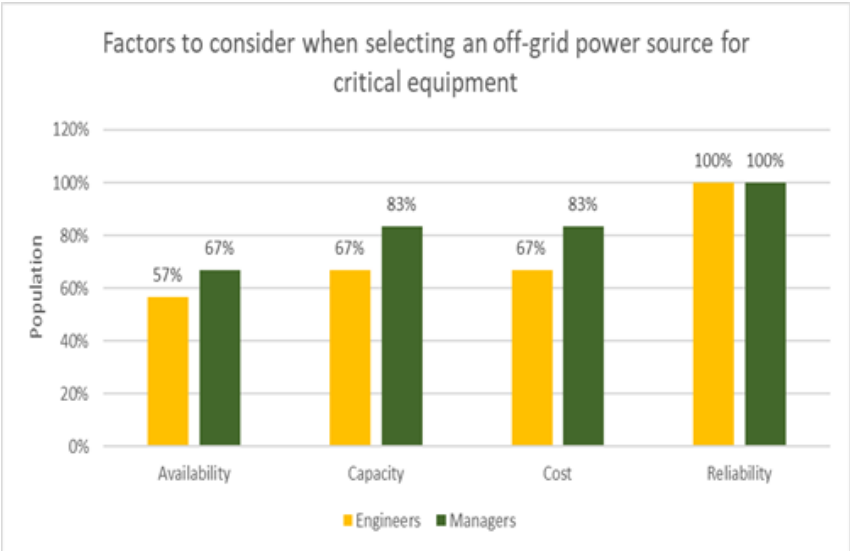


Figure 1. Important factors in selecting off-grid power source for critical equipment

The findings in Figure 2 underscore several key advantages of off-grid solar systems for powering medical instruments in remote areas. Firstly, they significantly reduce carbon dioxide and greenhouse gas emissions, aligning with global environmental sustainability goals. By harnessing solar energy, healthcare facilities can diminish their carbon footprint, promoting a cleaner environment. Additionally, transitioning away from fossil fuels eliminates associated health risks from air pollution. This shift promotes public health and well-being in the community.

Moreover, off-grid solar systems provide uninterrupted power supply, ensuring continuous operation of critical medical instruments. This reliability is crucial for maintaining timely diagnoses, treatments, and patient care in remote areas. Furthermore, these systems offer simplified installation and maintenance, reducing operational complexities and lowering overall costs. Compared to conventional power sources like diesel generators, off-grid solar solutions are easier to install and require minimal maintenance, making them more feasible for remote medical facilities. Overall, the survey emphasizes how off-grid solar systems fulfill key feasibility criteria, making them a practical and sustainable solution for powering medical instruments in remote healthcare settings.

Figure 3 data reveals that only about 30% of managers and engineers have utilized off-grid solar panels for powering scanners, such as X-Ray, MRI, and CT machines, indicating limited usage for larger, less portable equipment. Participants cited feasibility concerns, noting that solar panel installation is more practical for smaller, mobile devices like patient monitors. Similar trends were observed for other medical devices, such as syringe pumps and ventilators, where off-grid solar panel usage was more prominent for petite and portable equipment. Challenges include higher energy demands, space limitations, and cost considerations associated with larger equipment, making solar panels less feasible. This highlights the importance of tailored approaches for implementing off-grid solar systems based on the specific needs and practicalities of different medical devices.

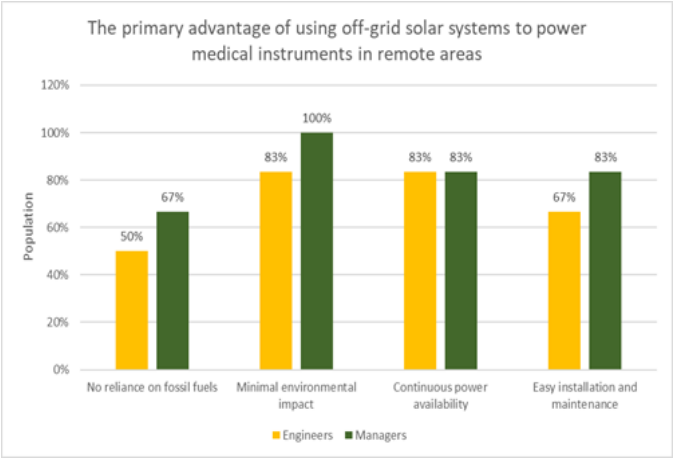


Figure 2. Benefits of using off-grid systems to power medical devices in remote areas

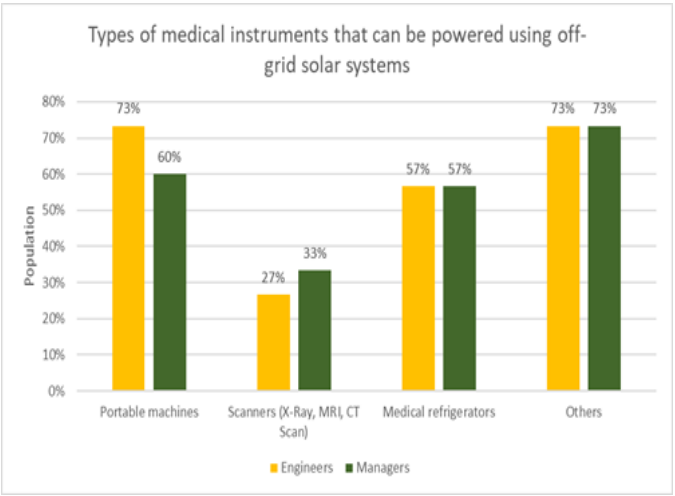


Figure 3. Medical instrument types powered using off-grid solar systems

The primary challenge identified by specialists in off-grid solar systems is the limited power supply on overcast days, as indicated by 90% of the respondents in Figure 4. This is followed by concerns regarding high installation costs and the need for qualified workers for system maintenance. However, only half of the specialists reported problems with system installation and finding maintenance experts.

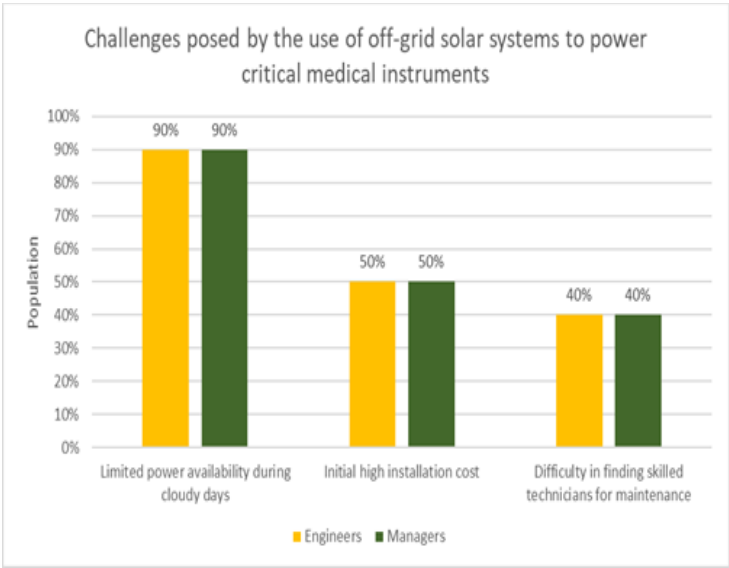


Figure 4. Challenges in using off-grid solar systems

Concerning the information presented in Figure 5, all participants acknowledged that the primary function of batteries in off-grid solar systems is to provide backup power during outages or system failures. This understanding highlights the crucial role of battery storage in ensuring the reliability of these systems for powering vital medical instruments. Furthermore, batteries play a significant role in stabilizing power output and preventing fluctuations. They also have the capacity to store excess solar energy, which can be utilized during periods of low sunlight, thereby contributing to the system's overall efficiency and effectiveness.

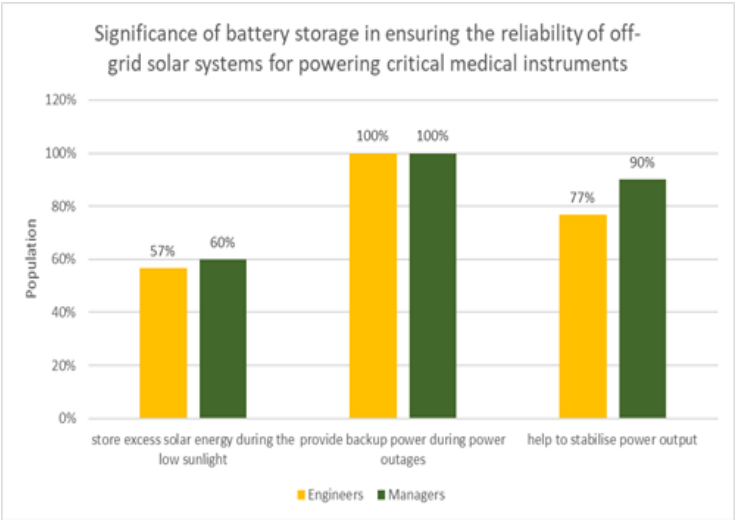


Figure 5. Battery storage's role in ensuring the reliability of off-grid solar systems

The respondents' endorsement of the system stems from its numerous advantages, including reliability, cost-effectiveness, environmental friendliness, and the ability to provide uninterrupted power supply to critical medical equipment. The system's performance in powering medical devices without any notable impact on their functionality further strengthens the case for its adoption. These findings suggest that the surveyed professionals recognize the potential of off-grid solar systems to revolutionize the way electricity is generated, particularly in the context of vital medical devices.

4.2 Findings and Discussion

The survey findings indicate that a significant proportion of the surveyed population, including engineers and managers, have previous experience and knowledge of utilising off-grid solar systems for medical equipment. The primary consideration when selecting an off-grid power source for critical equipment was reliability. Renewable energy sources were preferred due to their reliability and cost-effectiveness, while availability was considered less crucial. Cost-effectiveness was highlighted as off-grid solar systems were found to provide lower electricity costs compared to conventional systems. The lifespan of these systems was considered acceptable, as most medical devices have a lifecycle of less than ten years. Environmental benefits were also recognized, particularly in reducing carbon dioxide and greenhouse gas emissions. The challenges faced by specialists in this field included limited power supply on overcast days, high initial installation costs, and difficulties in finding qualified workers for maintenance. Storage batteries were suggested as backup power solutions. Climate change factors such as storms and cloudy days were seen as potential limitations affecting system functionality. However, the majority of participants reported no issues with the performance of off-grid solar systems.

It is worth noting that using off-grid solar panels for powering scanners like X-Ray, MRI, and CT scan machines was relatively uncommon according to the participants. Instead, they suggested that utilizing these systems for portable machines like ventilators may be more practical. Overall, the survey results showcase a favorable attitude towards the adoption of off-grid solar systems for medical instruments, pointing to a high demand for such projects. Participants emphasized the benefits of reduced reliance on fossil fuels and highlighted the lower environmental impact.

Dependability emerged as a top priority, with a majority expressing satisfaction regarding the performance of off-grid solar systems both during and after installation. In summary, the findings affirm the feasibility and viability of off-grid solar systems for powering critical medical instruments in remote or isolated areas. The combination of reliability, cost-effectiveness, and environmental benefits positions them as a dependable option. Despite existing challenges, the overall satisfaction and demand signal a positive outlook for the utilization of off-grid solar systems in healthcare settings.

5. Recommendations

Based on the study findings, the following suggestions are proposed to address challenges and enhance the efficiency of off-grid solar power system as a dependable and sustainable power solution for medical devices in electricity-deprived regions:

- 1) Promoting Environmental Benefits and Suitability
 - a) Clarity on environmental benefits: Clearly articulating the environmental advantages of off-grid solar power is essential to garner support and understanding from stakeholders.
 - b) Focus on power utilization: Emphasizing the optimization of power utilization for critical medical devices showcases a commitment to ensuring the reliability and sustainability of healthcare services.
- 2) Addressing Power Supply Limitations

- a) Maintenance and inspections: Regular maintenance and inspections are crucial for sustaining the efficiency of solar panels over time. This proactive approach ensures longevity and consistent performance.
- b) Battery storage integration: The recommendation to integrate high-efficiency battery storage systems is key for overcoming intermittent power supply challenges, providing a reliable energy source during periods of low sunlight.
- 3) Engaging Business Owners and Stakeholders
 - a) Increased attention from stakeholders: Encouraging business owners and stakeholders in health and renewable energy sectors to focus on the potential of off-grid solar panels underscores the need for collaborative efforts in addressing healthcare challenges.
 - b) Energy monitoring and management systems: Deploying monitoring systems reflects a commitment to ongoing improvement and efficiency, allowing for timely identification and rectification of issues.
- 4) Engagement with Local Stakeholders
 - a) Customization for medical facilities: Collaboration with local healthcare professionals and community leaders for customizing off-grid solar panel systems demonstrates an understanding of the unique needs of each medical facility.
 - b) Community involvement: Involving local stakeholders in the planning and implementation of solar projects ensures cultural relevance and community support.
- 5) Call for Further Research and Updates
 - a) Adaptability to local conditions: Recommending further research and updates aligns with the dynamic nature of economic and medical conditions in different regions, emphasizing the importance of tailoring solutions to local contexts.

By incorporating these recommendations and remaining adaptable to regional conditions, the objective of delivering reliable and sustainable power for critical healthcare needs in areas without electricity access can be achieved. This approach maximizes the potential of off-grid solar panels for medical devices and contributes to improved healthcare outcomes in underserved regions.

6. Conclusion

This paper underscores off-grid photovoltaics as a viable and low-maintenance power solution for critical medical instruments in resource-limited settings. It demonstrates that off-grid solar systems provide sustainable energy for essential medical devices, such as patient monitors and ventilators. The utilization of off-grid solar technology enhances healthcare delivery in remote areas, particularly in developing countries facing frequent electricity blackouts. This technology establishes a reliable energy source for critical medical instruments, ensuring healthcare provision in challenging environments and improving access in rural areas with limited fuel availability.

The implications of these findings underscore the significance of off-grid solar technology for enhancing healthcare access and delivery in resource-limited settings. By addressing challenges like limited electricity access, inadequate infrastructure, and high maintenance costs associated with conventional electricity generation methods, investing in off-grid solar systems enables healthcare facilities to improve patient outcomes and contribute to community development. Prioritizing off-grid solar power for medical devices is crucial, requiring comprehensive battery management knowledge and engagement with local stakeholders to ensure reliable power supply and successful integration, thus optimizing healthcare services sustainably. However, further study and development are necessary to optimize off-grid solar systems for specific medical instrument requirements, enhance energy storage capabilities, and address cost barriers. Collaboration between the health sector, renewable energy industry, and local communities is crucial for the effective deployment and sustainability of off-grid solar solutions. Leveraging the potential of off-grid solar technology can enable healthcare providers to establish a more resilient and sustainable healthcare infrastructure in resource-limited regions, ultimately enhancing the well-being and quality of life for underserved populations.

This study recommends two strategies to overcome power supply limitations and high installation costs. Firstly, utilizing high-efficiency battery storage systems and conducting regular maintenance can address power supply challenges. These systems store excess energy during optimal conditions, ensuring a consistent power supply for critical medical devices, even in adverse weather. Additionally, adhering to industry standards and regulations is crucial to establishing the system's validity, safety, and compatibility with medical equipment. This reinforces the system's credibility in critical healthcare settings, promoting reliable and effective operation. In summary, the evaluation of the off-grid photovoltaic system highlights its reliability and sustainability in providing power for critical medical instruments in areas without access to electricity. Adhering to the recommendations outlined in this study can achieve optimal patient care in resource-limited settings. Additionally, these measures contribute to the conservation of the environment and the reduction of pollutants, aligning with the goals of the renewable energy industry. Future studies should scrutinize critical medical devices' performance during power outages and further development of off-grid solar systems.

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