

Ensuring Reliable Healthcare in Rural and Remote Areas: The Role of Decentralized Solar Energy in Maternal and Child Health using HHFA Framework – A Systematic Review and Meta-Analysis

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ABSTRACT

Introduction: An unreliable energy supply in rural and remote healthcare facilities leads to poor quality of health-services affecting health-outcomes. Energy supplied to healthcare facilities has a significant impact especially on maternal-child-health and emergency care. The present study aims to explore the impact of integrating solar energy in rural and remote healthcare settings on maternal and child health outcomes along with Emergency Obstetric care (EmOC) using Harmonised-Health-Facility-Assessment (HHFA) framework. The HHFA framework measures service-availability, readiness, quality-of-care and management in healthcare.

Methods: The steps in this process were conducted according to the PRISMA (Preferred-Reporting-Items-for-Systematic-reviews-and-Meta-Analysis) guidelines. The PubMed, Science-Direct, the Cochrane Library were searched including secondary references and the grey literature was retrieved through research-and-policy-reports. A total of 144 studies were identified, of which 131 were excluded being not in scope of present study. Further, 4 studies were extracted using grey literature, and finally, a total of 17 studies including 5 studies for meta-analysis were considered as per inclusion criteria across LMIC's.

Results: The present Systematic review showed improved Maternal and child health-outcomes adhering with the HHFA framework due to solar-based interventions with improved vaccine-storage-management, lighting, and ventilation, resulting in reduced infant and maternal mortality. The Meta-analysis comparing the conventional sources of energy to solar-powered-oxygen-supply for child healthcare indicates the presence of substantial heterogeneity and variation in risk difference estimates across the studies (N=33224; RD=0.03; 95%CI 0.01, 0.05; p<0.001) depicted through forest and funnel plots. The Meta-regression-analysis indicates a positive impact of duration on the effect size indicating the factors responsible for heterogeneity (regression-coefficient r=0.612; 95%CI 0.27, 0.93; p<0.005) emphasizing on the need for solar-powered-oxygen supply over the conventional sources.

Conclusion: The study underscores the transformative impact of integrating solar-energy in rural and remote healthcare-facilities, advocating adoption of climate-resilient technologies in the form of decentralised solar energy solutions as a policy imperative to ensure equitable healthcare-services.

Key words: Decentralised solar energy; Primary healthcare; Maternal child health; Universal health coverage; Sustainable development goals

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INTRODUCTION

Close to 1 billion populations in low-and-middle-income-countries (LMICs) are relying on healthcare facilities heavily dependent on unreliable energy sources or no energy access at all. The unreliable energy or electricity supply not only endangers human life but also restricts the access to healthcare services in rural and remote areas, deteriorating vaccination storage, increased fuel cost, and reduced usage of healthcare technologies.¹ Even the accessibility of power does not guarantee its reliability particularly in primary healthcare centres (PHCs) of remote and rural areas serving as the first point of contact in any healthcare emergencies.² Majority of the PHCs in LMICs are struggling with disrupted electricity supply as around 72% of facilities have reported the issue of unreliable supply of energy.³

Due to the lack of continuous energy supply, the majority of women and children are bearing the double-burden of healthcare fragility in LMICs. The lack of continuous energy supply is also cited as major reason behind the increased maternal and under-5 mortality. During pandemic, 19% of the clinical cases required oxygen supply; however, only 7% have reported electricity connectivity leaving behind 12% with restricted access to electricity.⁴ The literature highlighted that basic medical-facilities such as ventilators, oxygen supplies, and basic life support devices are often non-functional or comes with additional financial and logistic challenges.⁵ This further restricts the medical capacity to respond to infectious diseases and other healthcare emergencies in rural and remote settings. Electrification of healthcare facilities especially in rural and remote areas of LMICs has not received the needed attention despite the significant coverage scope allowing for equitable vaccine-delivery, availability of emergency-obstetric-care (EmOC), and providing emergency and trauma-care. The lack or restricted access to electricity has been a major bottleneck in providing necessary healthcare facilities especially for the maternal and child healthcare (MCH) in these settings.⁶ Power outages severely affect the functioning of rural healthcare-facilities such as PHCs, leading to compromised quality of care, restricted service-delivery, and limited intake of in-patient, denying needed care in case of immediate emergencies for pregnant women, and children. These disruptions not only restrict ability to access distant healthcare facilities but also increase their dependency on either the inadequate home-based treatments or forgone care.⁷ The studies also indicated that supply side barriers such as infrastructure including the electrification of the PHCs, proximity of healthcare facility and functioning of medical equipment were significantly associated with the improved MCH outcomes.^{8,9}

Energy shortage or electrification results in a declined percentage of Institutional-birth in remote healthcare facilities. Studies also^{8,9} demonstrated that inadequate electricity supply in these facilities significantly reduces overall service utilization creating supply side barriers. Also, if essential facilities such as electricity, water, and toilets along with the limited number of beds, essential obstetric drugs, medical equipment and communication infrastructure are not available, it affect the affordability, utilization, quality of care in remote facilities.⁸⁻¹⁰ Establishing a reliable energy strategy specifically tailored for rural areas is crucial for achieving sustainable improvements in MCH outcomes. Solar energy, when integrated across various applications holds substantial promise for enhancing healthcare infrastructure, affordability, service-readiness, and quality-of-care. Conventional methods of energy

distribution have often proven unreliable and costly, particularly in catering the needs of rural healthcare facilities in many LMICs.¹⁰

Policy efforts aimed at improving MCH outcomes in LMICs have traditionally focused on direct healthcare indicators such as expanding healthcare infrastructure, training healthcare workers, and improving healthcare-financing. The Global Strategy for Women's, Children's, and Adolescent Health (2016-2030) has recognized that achieving improved MCH health goals necessitates creating an enabling environment integrating health with other sectors, particularly basic infrastructure such as electricity.¹¹ The WHO also underscores that electricity plays a critical role as a major enabler in achieving universal-health-care (UHC). The availability of consistent electricity supply and voltage stability not only improves healthcare availability, readiness and delivery but also has broader welfare implications. Supply of reliable electricity is paramount in establishing and maintaining high-quality healthcare infrastructure, functioning of medical equipment's, access to care, supporting in improved MCH outcomes. The availability and quality of healthcare-services play a crucial role in not only achieving the UHC but also advancing towards health-related SDGs. Various life-saving interventions for MCH care which are crucial for healthcare provisioning cannot be effectively carried out in the absence of a reliable electricity supply.¹²

Standardized assessment tools developed by organizations such as the WHO, World Bank, and USAID are widely recognised as gold standards for evaluating healthcare outcomes especially for MCH services including tools such as WHO's Service Availability and Readiness Assessment (SARA). For present systematic review, the Harmonized Health Facility Assessment (HHFA) which is an extended version of WHO's SARA (Annexure-1), has been taken as a base for comprehensive assessment of healthcare facilities especially in rural settings for MCH outcomes. The HHFA provides accurate and objective data on the availability of healthcare services and also assesses the facilities' capabilities to deliver these services at the required quality standards.^{13,14} The integration of renewable photovoltaic energy into rural health electrification frameworks is critical, particularly for improving the MCH outcomes and advancing for UHC in LMICs. This necessitates establishing a national policy framework for improving the MCH outcomes and overall healthcare service delivery in the rural and remote settings. It supports vital functions such as powering vaccines, refrigeration, lighting, communication-systems, medical-equipment, and ensuring clean water supplies and sanitation.¹⁵ As limited numbers of studies are available addressing solely the impact of solar energy on the improved MCH outcomes, present systematic review-and meta-analysis aims to understand the impact of decentralised solar energy interventions in rural and remote healthcare facilities using HHFA framework.

METHODS

Literature Search

Search strategies were designed and conducted according to the Preferred-Reporting-Items-for-Systematic-Reviews-and-Meta-Analysis (PRISMA) reporting guidelines.^{16, 17} The databases such as PubMed, Science-Direct, the Cochrane library, Web-of Science and the grey literature were retrieved through research and policy-reports from inception to December, 2023. Secondary references were

searched and reviewed along with reference lists of the articles. The key search terms used were maternal-and-child-healthcare, primary-healthcare and solar-energy. Keywords were identified through PICO approach P-population (((Primary healthcare) OR (rural population)) OR (maternal and child healthcare), I – Intervention (((Solar energy) OR (solarisation)) OR (renewable energy), C – Control (((Grid connected) OR (electricity)) OR (fossil fuel)) OR (diesel generators) and O – Outcome (((health outcome) OR (maternal and child healthcare)) OR (service readiness and service availability) (provided as supplementary file). This systematic review protocol title has been registered with the International Prospective-Register-of-Systematic-Reviews (PROSPERO) database (registration number: CRD42023415763).

Selection criteria

Studies highlighting the impact of solar energy intervention on the MCH outcome at the rural/remote healthcare centres compared to the existing conventional form of grid electricity supply were included for the present study. Further, the HHFA, a comprehensive health facility survey by WHO which is used to assess the availability, readiness, quality of care of health facility services and management was used as a theoretical and assessment framework. Only those studies which examined the following were included - remote and rural health centres, primary healthcare facilities, solar energy, maternal and child healthcare, quality and availability of healthcare services, and LMIC's. The searches were carried out regardless of language and publication status. Studies must report information on intervention of solar powered energy or renewable energy in rural and remote healthcare facilities as an intervention/exposure while grid connected, electricity, fossil fuel, diesel generators-based power supply was included as a comparison group. The primary outcome includes the health outcomes pertaining to maternal and child health care, service readiness, service availability, quality of care and management. We included mixed design and pre-post studies. Studies on animal and rodents, case reports/ case studies, editorials, commentaries/viewpoints/opinion, conference abstracts, rapid/scoping reviews and studies outside of LMICs were excluded.

Data Extraction

Titles and abstracts were assessed by the three independent reviewers for potential relevance. Prior to the screening of title and abstracts, a screening form was developed based on the selection criteria. Two independent reviewers screened all potentially relevant full-text articles (all articles tagged as “yes” or “maybe” during the previous stage). Disagreements (e.g. “yes” or “maybe” and selected “no”) were resolved by consensus or a third author of the research team. Using study-specific data forms, predetermined data were extracted for each study. Data extraction includes study characteristics; study design; population characteristics; details of control or comparison groups (if available); renewable, solar energy; rural and remote settings and maternal and child health outcomes data; and study year. One reviewer has extracted all information, which was verified by a second reviewer. Findings were resolved through consensus or a third reviewer. In case of incomplete or missing information, the contact was initiated with respective authors through email over a period of one month.

All processes ensured that bias was minimized while deciding whether to include or exclude certain studies based on the application of objectives, selection criteria, independent reviewers and conflicts resolved through a third reviewer. A PRISMA flow chart indicates the number of studies which were included or excluded at each stage based on the integration of solar energy on healthcare outcomes through a decentralised approach. The studies considered under inclusion criteria highlight the pre and post intervention impact of solar energy over the existing and conventional health technologies that had a positive impact on the type of services available and provided for MCH in rural and remote healthcare facilities. Further, the WHO, HHFA tool was followed for measuring healthcare outcomes at a health centre based on service availability, service readiness, quality of care and management as parameters. Main reasons for exclusion during the full-text screening stage were also documented.

We presented study outcomes in quantitative format in a series of summary of findings tables, organized by types of data. For MCH needs based on the solar-powered-oxygen-supply data was pooled by using meta-analysis techniques. The Joanna Briggs Institute critical appraisal checklist for studies reporting pre-post intervention impact of solar-powered-oxygen-supply was used to determine and control the articles' quality (Joanna Briggs Institute, 2011). This instrument was used for quality assessment of studies, which contains eight questions responded via three options; i.e. yes, no and not-applicable. The instrument aims at evaluation of the methodological quality of articles and determination of errors in studies, designs and data analyses. The results of the quality of studies showed that all studies had quality.

Statistical Analysis

The major focus of the study was to explore the impact of solar energy intervention on rural and remote health-facilities with emphasis on MCH outcomes. An estimation of the overall effect size regarding the impact of solar energy on MCH outcomes which is the variation between the pre and the post intervention groups, referred to as the ratio difference (RD) and calculated for the included trials. The effect size, which is the difference between non solarised/electricity driven over the solarised healthcare outcomes in terms of MCH services, was considered for each included study.

Overall effect size with 95% confidence interval (CI) follows chi-square distribution with $k-1$ degrees-of-freedom (df) where k is the number of studies. Estimating the variance (T^2) between studies, parameters I^2 quantified the percentage of total variation in study estimates due to heterogeneity rather than sampling error. The heterogeneity (variance in studies) of results was depicted in the form of forest plot, typically representing a blob in the middle of the 95% CI that characterizes the RD estimates. The forest plot presents graphical representations of the results. The horizontal line in the middle represents the overall effect size and the pooled/combined result of the RD in the effect size denoted by diamond on the plot representing 95% CI for each study / subgroup for a combined data. The overall effects size of these results was assessed for sampling error (homogeneous, $t^2 = 0$) (Borenstein et al., 2010; Mendu et al., 2019). A random-effects meta-analysis was applied to obtain the pooled effect size with 95% CI (heterogeneous, $t^2 > 0$). The parameter I^2 quantifies the extent of heterogeneity from a collection of effect sizes, which is interpreted as approximately the percentage of the total variation in study

estimates because of heterogeneity rather than sampling error.

The size of the diamond reflects the weights assigned to each study and the horizontal line through the diamond represents the point estimates of the prevalence rate. The vertical line represents the null effect line indicating no difference between the interventions. An $I^2 > 50\%$ indicates a significant heterogeneity between interventions; Meta regression analysis was performed to detect the source of heterogeneity of impact of solar energy on maternal and child healthcare. Statistical analyses were performed with Review Manager (RevMan) software version 5.4, IBM SPSS version 23, and STATA 14 software.

RESULTS

The PRISMA flow diagram outlines the process of literature search on the impact of solar energy in rural and remote healthcare facilities focusing on woman and child healthcare outcomes with subsequent screening from the existing literature (Fig.1).

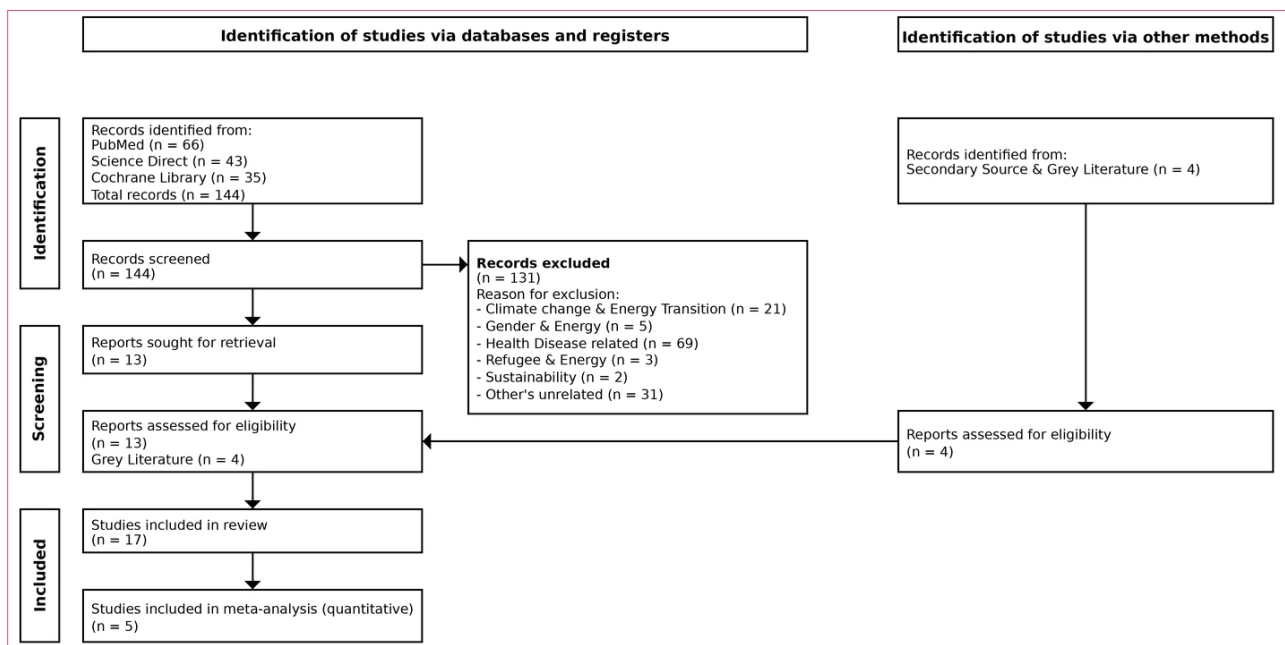


Figure 1. PRISMA Flow diagram of study selection for Systematic Review

PRISMA flowchart explains the study collection method for the systematic review. The diagram shows the number of studies identified through database searches, the number of studies screened for eligibility, the number of studies excluded and the final number of studies included for the review along with reasons for exclusion.

The search initially yielded a total of 144 potentially relevant studies which were screened for their potential relevance and inclusion, of which 131 studies were excluded as they were not considering pre-post solar energy intervention, availability, readiness and quality of healthcare, and MCH outcomes. Based on the PICO's and search strategy, the studies were retrieved through databases and search engines. Considering appropriate keywords and Boolean algebra search strategy (OR/AND) the

studies were identified. The studies that included the integration of solar energy for rural and remote health centres/facilities and its equipment/interventions were considered under inclusion criteria. Through PubMed a total of 66 papers were retrieved through search strategy in which 6 studies were considered as per inclusion criteria and remaining 60 studies were excluded through title and abstract screening. Through Science-Direct, a total of 78 studies were retrieved and 7 studies were considered as per the inclusion criteria. Through Cochrane-Library 35 studies were screened, however none were considered as it doesn't contain any interventions pertaining to solar energy on MCH outcomes. Also, 4 studies were identified through grey literature highlighting through research reports, dissertation and policy briefs. Finally, 17 (Rokicki et al., 2019; Rokicki et al., 2021; Javadi et al., 2020; Cohen et al., 2019; Conradi et al., 2019; Nyende et al., 2015; Graham et al., 2017; Franco et al., 2017; Bhattacharya 2021; Suhrie et al., 2018; Shastry & Rai 2021; Soto et al., 2022; Mani et al., 2021; Irwin et al., 2022; Ramji et al., 2017; Concessao et al., 2023; Jimenez & Olson 1998) studies were eligible as per the inclusion criteria for further data extraction and analysis. A total of 17 studies were finalised for the systematic review (depicted in Fig. 1 and Table 1), and five statistical studies reporting quantitative data were considered for meta-analysis.

Five studies were evaluated through statistical analysis by using forest plot; funnel plot and Meta regression comparing the solar energy intervention and conventional energy interventions. From the forest plot (Fig. 2), the results indicate that the RD of Solar-Powered-oxygen delivery pooled an estimate of $N=33224$; $RD=0.03$; (95% CI 0.01, 0.05; $p<0.005$). The random-effects model was used for the analysis, and the heterogeneity statistics showed a statistically significant heterogeneity ($I^2 = 82\%$) that indicates variation in RD estimates across the studies.

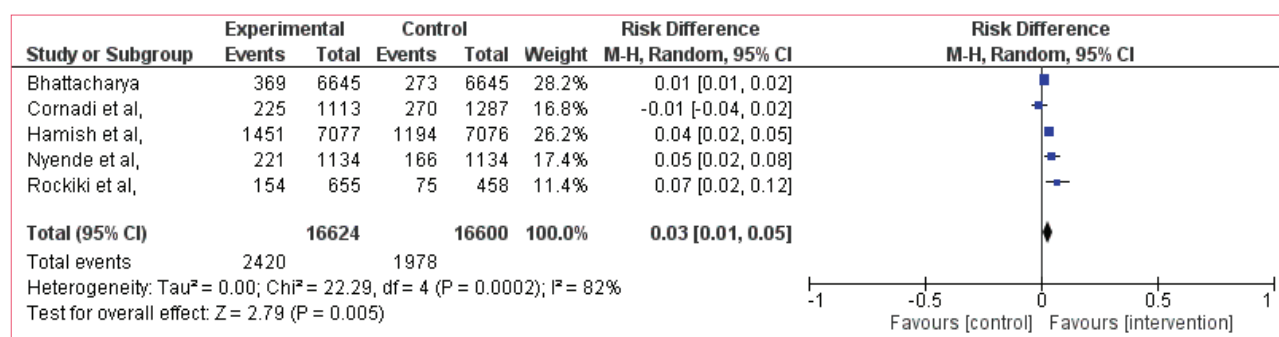


Figure 2. Variation in risk difference estimates for oxygen delivery through Meta-Analysis

The meta-regression analysis aimed to identify sources of heterogeneity among the included studies by examining moderator variables such as study duration, sample size and effect size. The findings indicated a significant impact of duration on the effect size ($r=0.612$; 95%CI 0.27, 0.93; $p<0.005$), suggesting that duration plays a role in contributing to the observed heterogeneity among studies. (Fig. 3) visually represents this relationship, showing a trend where longer durations correlate with higher effect sizes. This trend is illustrated by an increase in the logarithmic values of the event rate across the data points.

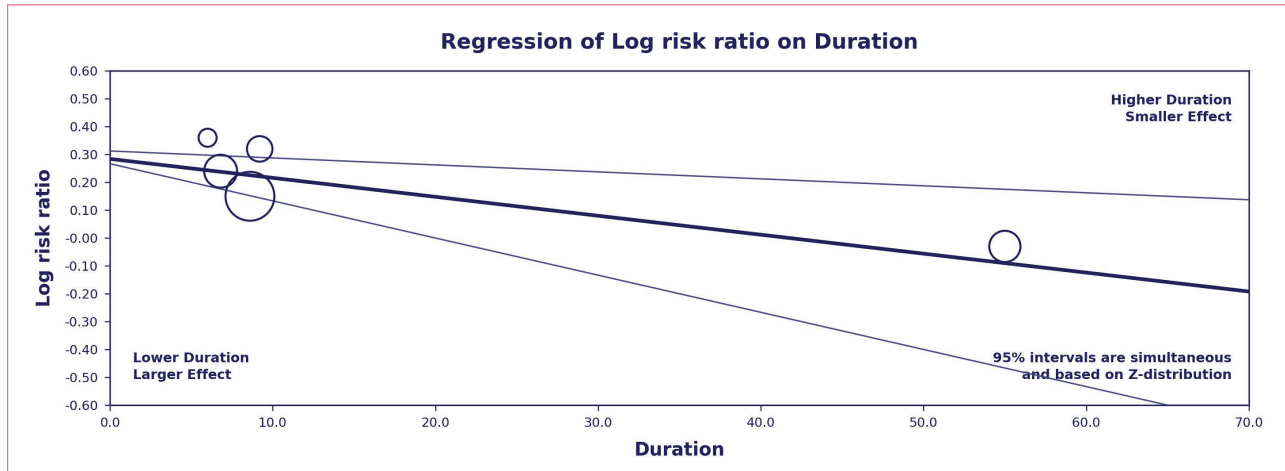


Figure 3. Graphical Representation of relationship between the predictor and the outcome variable Egger's Regression

A funnel plot (Fig.4) is a graphical tool frequently employed in meta-analysis to visually evaluate the potential for publication bias. It consists of a scatter plot where the effect size (or log of the effect size) of each study is plotted against the standard error (or sample size) of the estimate. In the absence of publication bias, the plot typically exhibits a symmetrical funnel shape. The Funnel plot (Fig. 4) was symmetrical, indicating the probable absence of publication bias, as the p-value for Solar-Powered oxygen delivery is 0.79. However, for estimating the publication bias using Egger's weighted regression for estimating the publication bias was not employed as only five studies has been included for the Meta-analysis reporting quantitative data on solar powered interventions on MCH outcomes as per the HHFA indicators. A minimum of 10 studies reporting quantitative data were needed for using Egger's weighted regression.

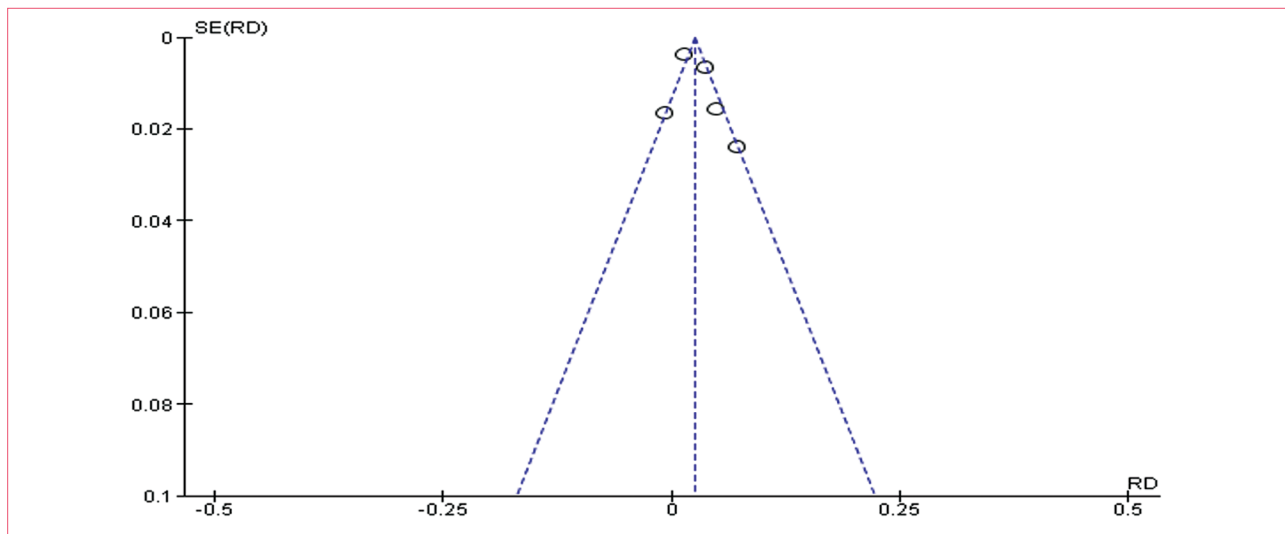


Figure 4. Graphical representation of Funnel Plot interpreting No Publication Bias

Figure Label: The funnel plot illustrates the relationship between study size (X axis) and treatment effect (Y axis) across the studies included in meta-analysis. The plot is symmetrical, suggesting the absence of significant publication bias.

Table 1. Characteristics of the included studies for Systematic Review

Search Engine	Sr. No	Research/Article/Study/Report Title	Study Type	Authors	Journal Name	Objective of the Study	Health Facility Level	Outcome Measures
PubMed	1	Impact Of Solar Light and Electricity on The Quality and Timeliness Of Maternity Care: A Stepped-Wedge Cluster-Randomized Trial In Uganda	Cluster-Randomized Trial	Rokicki et al 2021	Global Health Science and Practise	To study impact of solarisation on maternal and child health	Primary Health Facilities	Access to reliable energy is included in larger efforts to improve quality of care via systematic changes to health systems
	2	Implementation Research on Sustainable Electrification Of Rural Primary Care Facilities In Ghana And Uganda	Normalisation Process Theory (NPT)	Javadi et al 2020	Health Policy and Planning, Oxford	1. To capture changes in service availability and readiness, 2. To describe changes in community satisfaction and use, and 3. To Examine the implementation factors of sustainable electrification that affect these changes	Rural Health Facilities	Availability of sustainable energy in rural health facilities is associated with improved community satisfaction of available health services
	3	Shedding Light on Quality Of Care: A Study Protocol For A Randomized Trial Evaluating The Impact Of The Solar Suitcase In Rural Health Facilities On Maternal And Newborn Care Quality In Uganda	Randomized Trial	Rokicki et al 2019	BMC Pregnancy and Childbirth	To evaluate the impact of solar suitcase on reliability of light, quality of obstetric and new-born care and health workers satisfaction	Rural Health Facilities	Reliability and quality of light during intrapartum care is very essential and sustainable energy like solar is helping to solve the issue.
	4	Solar-Powered Oxygen Delivery For The Treatment Of Children With Hypoxemia: Protocol For A Cluster-Randomized Stepped-Wedge Controlled Trial In Uganda	Cluster-Randomized Stepped-Wedge Controlled Trial	Conradi et al 2019	BMC (Trails)	To demonstrate efficacy of solar powered oxygen in children hospitalised with acute hypoxemic respiratory illness	Rural Health Facilities	Lifesaving, cost effectiveness interventions such as solar-powered oxygen could represent an important tool for the improvement of global child survival.
	5	Solar powered oxygen delivery : study protocol for Randomised Control Trial	Randomized Control Trial	Nyende et al 2015	BioMed Central (Trails)	To demonstrate the non-inferiority of solar powered oxygen delivery relative to standard oxygen delivery	Rural and Remote Health Facilities	Significant reduction in the number of children dying of pneumonia may be realised with the intervention of solar powered oxygen delivery to provide supportive therapy with oxygen globally.
	6	Improving oxygen therapy for children and neonates in secondary hospitals in Nigeria: study protocol for a stepped wedge cluster randomised trial	Stepped Wedge Cluster Randomised Trial	Graham et al 2017	BioMed Central (Trails)	To understand how to most effectively implement oxygen systems in complex, resource limited environments.	Remote and Resource Constrained Environment	Reduction in pneumonia case fatality and neonatal care facility through solar powered oxygen therapy with policy implications to scale this globally to reduce child deaths.

Table 1 Continued.

Search Engine	Sr. No	Research/Article/Study/Report Title	Study Type	Authors	Journal Name	Objective of the Study	Health Facility Level	Outcome Measures
Science Direct	7	A Review of Sustainable Energy Access And Technologies For Healthcare Facilities InThe Global South	Review Study	Franco et al 2017	Elsevier	To estimate the energy needs of different healthcare facilities as a function of patient capacity and service provided.	Health Facilities	Healthcare facilities should steer towards other energy sources, notably renewable energy, solar energy being easily deployable with operation and maintenance.
	8	Impact Of Solar Electrification On Health Care Of Rural Women: A Study InPoundi – Uproda Block Of Chhattisgarh	Correlation-al Study	Bhat-tacharya 2021	International Journal of Education, Modern Management, Applied Science & Social Science (IJEMMASS)	[To study about the improvement in medical facilities in the rural areas of Chhattisgarh through Solar Electrification. To study the impact of solar electrification on the health of pregnant women in context of safe child delivery in rural areas of Chhattisgarh State.	Primary and Community Health Centres	Solar electrification is not only providing clean and green energy from renewable sources but also contributing to social issues like the health of rural women and child health.
Cochrane Library	9	The Role of Energy in health facilities: A Conceptual Framework and completely data assessment in Malawi	Conceptual Framework Study	Suhirir et al 2018	PLOS ONE	To explore how characteristics of electricity supply affect distinct energy uses in health facilities	All Health Facilities	The framework conceptualises the role of energy in health facilities in a detailed manner with solarisation being critical for providing services.
	10	Reduced health service's at under electrified primary healthcare facilities: Evidence from India	Empirical Study	Shastry & Rai 2021	PLOS ONE	To estimate the relationship between levels of electricity access and the quality of basic health services delivered at primary health centres (PHC)	Primary Health Centres (PHC's)	Lower level of electricity access at primary health centres is disproportionately associated with adverse effects on women's access to safe and quality healthcare
	11	Solar Energy Implementation for Healthcare Facilities in Developing and Underdeveloped Countries: Overview, Opportunities & Challenges	Review Study	Soto et al 2022	MDPI	To provide literature review on the solar energy applications in underdeveloped and developing countries with specific focus on healthcare facilities	Rural Health Facilities	Solar Energy plays a critical role in providing healthcare services to remote areas making access to quality healthcare
	12	Ensuring Access, Sources & Reliability at Primary Health Centres in India and Effect on Service Provision: Evidence from Two National Wide Survey	Review Study and Survey Study	Mani et al 2021	Indian Journal of Community Medicine	To assess the status and change in electricity access, sources and reliability at PHC's. To understand the effect of regular electricity supply on health service provision and on workforce availability and retention	Primary Health Centres (PHC's)	Access to reliable energy has potential to accelerate India's progress towards UHC and help achieve the goals and targets of national health policy
	13	Effects of Energy Shortages on Institutional delivery in India	Empirical Study	Irwin et al 2022	Medrxiv (BMJ)	To estimate the association between energy shortage and institutional delivery rates using logistic and multinomial regression	Rural Health Facilities	Revealed that energy shortages were a significant predictor of reduced odds of institutional delivery.

Table 1 Continued.

Search Engine	Sr. No	Research/Article/Study/Report Title	Study Type	Authors	Journal Name	Objective of the Study	Health Facility Level	Outcome Measures
Grey Literature	14	Powering Primary Healthcare through Solar in India: Lessons from Chattisgarh	Evaluation Study	Ramji et al 2017	Council on Energy, Environment & Water (CEEW)	To understand the synergy between electricity access and delivery of healthcare services. To evaluate the impact of installed solar PV systems addressing gaps in access to electricity. Assess the gaps in the transition to higher standard of primary healthcare in Chhattisgarh	Primary Health Centres (PHC's)	The insight from this study encompasses several areas - electricity access and health, the role of solar energy in cold chain management and neonatal health has led to positive impact. Also highlighting the aspect of operation and maintenance of the solar system for health.
	15	Energizing health: accelerating electricity access in healthcare facilities	Report	NA	WHO, World Bank, IRENA & SEforALL	The report highlights the aspect of energy accessibility and reliability at healthcare facilities through renewable energy planning, implementation and evaluation.	Rural Health Facilities	The insights from the reports will help in greater scalability of the models implemented under health energy nexus from a broader policy influence for integration of renewable energy for health facilities across the world.
	16	A spoonful of solar to help the medicine go down: Exploring synergies between healthcare and energy	Report	Concessao et al 2023	WRI (World Resource Institute)	To explore the role of Decentralised Renewable Energy (DRE) in rural health facilities and its linkages to provisioning of healthcare services, especially underserved populations.	Rural Health Facilities	The findings have indicated decentralised solar energy interventions have a role in addressing constraints across the six health system building blocks that WHO identifies as critical to strengthening health systems through service delivery, health workforce, information, medical products, vaccines and technologies, financing, leadership and governance.
	17	Renewable Energy for Rural Health Clinics	Report	Jimenez & Olson 1998	National Renewable Energy Laboratory	To share broad understanding of the technical, social and organisational aspect of health clinic electrification	Rural and Remote Health Facilities	The report presents highlights of solar electrification for rural healthcare from micro level to macro level understanding.

DISCUSSION

The present systematic review and meta-analysis has highlighted the impact of solar energy interventions on women and child healthcare particularly on the maternal-and-child-health outcomes in a rural and remote healthcare facilities. The finding from the study underscores the instrumental role of decentralized solar energy on the MCH outcome that is both life-saving and critical across

LMICs where energy acting as a catalyst. Further, the study through meta-analysis has found that solar intervention specifically focused on child healthcare in case of emergency healthcare service delivery such as oxygen supply has significantly improved the health-outcomes compared to conventional sources of oxygen concentrators. Hypoxemia commonly termed as low blood oxygen level is one of the complications in pneumonia, malaria, sepsis and pre-term birth, without oxygen therapy, it can lead to death. Oxygen support immediately at the birth helps in reducing brain damage that can even lead to death of the baby. Oxygen supply is very critical for life saving of the new-born and solar energy acts as a catalyst with reliable power supply needed for the oxygen therapy.

The energy supply plays a critical role in improving the access, availability, and overall utilization of healthcare services.^{3, 4} The findings of the present study have reported significant reduction in the burden of infant mortality rates (IMR) with the post solarization interventions in the rural and remote healthcare facilities. It was recorded that the IMR has reduced up-to 35% (5.0% - 3.2%) in cases of post-solar implementation in these areas.¹⁸⁻²⁰ These studies highlight on the critical role of solar-powered oxygen therapy in reducing child mortality devoted to conditions such as hypoxemia and pneumonia in rural and remote areas of Africa, Asia and other LMICs. The studies conducted in similar settings^{21, 22} also underscore the importance of basic energy access, such as lighting, ventilation, water facility in enhancing healthcare delivery.

Present Meta-Analysis also²³ emphasizes that solar energy electrification not only provides clean and renewable energy but also contributes in addressing the social issues such as MCH Care in rural areas. Other studies have also reported that MCH outcomes especially from the supply side barriers are major bottleneck in service availability, and readiness affecting the utilization of services.¹¹⁻¹³ In case of unreliable power supply or low lighting, there will be complications in child delivery, resulting into adverse birth outcomes, not only affecting the child health but also increasing the risk of contamination, and infections during and after delivery.^{11, 14}

Present study also elucidates how standalone solar systems implemented at PHCs have significantly improved the MCH outcomes. Overall, the transition to sustainable energy in rural healthcare settings not only significantly enhances the quality and availability of care, but also addresses the key concerns such as service-readiness, quality-of-care, and management, as evident by the present study.²⁴ In Sub-Saharan-African nations, enhancing accessibility and reliability of basic energy access, coupled with solarisation of critical devices, has led to reduced mortalities and improved health outcomes within the communities for both mothers and children.²⁵

The solar energy supply can be a key element in immunization which is crucial for the health of infants and mothers globally, especially in rural and remote healthcare facilities. The reliable solar energy supply plays a critical role across the entire vaccine process from production to storage and usage during crucial vaccination periods. This review supports the effectiveness of solar energy intervention on improved healthcare service utilization, addressing supply side barriers and MCH outcomes adhering with the HHFA indicators.

Limitations

Most of the included studies had short period follow up i.e. less than 6 months to a year limiting the ability to assess the long-term effectiveness of the intervention. Further, given the limited literature available on the impact of decentralised solar power on MCH outcomes reporting the quantitative data or findings, this study may not indicate accurate risk of publication bias. However, there is a need for further research to explore the long-term impact with operations and maintenance of energy systems.

CONCLUSION

The present systematic review and meta-analysis concludes that electrification of healthcare facilities in rural and remote areas through decentralised solar energy interventions aids in the reliability and improved MCH outcomes. The study also uses the HHFA framework, emphasising on the role of solar powered electrification of PHCs in remote setting for improved service availability, enhanced service readiness for any medical emergencies, strengthened quality of care and efficient health data management.

The key findings from the study highlights towards the transformative changes in pre and post solarisation interventions on MCH outcomes. The quality of care has improved in terms of reliability of lighting, ventilation and water facility during the delivery and post-delivery care support such as baby warmer for maintaining temperature, the oxygen support for the new-borns. The role of reliable energy supply through solar plays a critical role in vaccine management and storage for maintaining the potency level for immunization support for EmoC. The healthcare data management became more efficient leading to proper record management. The solar integrated electrification has been one of important models that directly show impact on health care services supporting the activities of healthcare providers with enhanced quality of service. By integrating solar energy, healthcare facilities can be prepared to better respond to the challenges through emergency preparedness. The solar powered energy provides readiness for unforeseen events related to climate change and pandemic, making rural and remote healthcare systems more resilient and self-sufficient. Policy efforts should prioritize integrating clean solar energy into healthcare planning, prioritising for enhancing scalability and sustainability. A successful model, supported by governments and other non-governmental organizations in LMICs, demonstrates the potential for decentralized renewable energy (DRE) solutions to sustain PHCs in the remotest corners of the world. Initiatives such as Sustainable Energy for All, which has solarized thousands of PHCs in Africa, set a benchmark for global adoption of DRE. These efforts align with Sustainable Development Goals (SDGs) 7 (Affordable and Clean Energy), 3 (Good Health and Well-being), and 13 (Climate Action), ensuring a healthier and sustainable future. The future research should explore the narrative approach and lived realities of the healthcare workers to build more evidence for policy influence and wider replicability of healthcare electrification model across the globe. However the initial cost of setting up the solar is assumed to be high, the impact that it creates is lifesaving that is both moral imperative and a strategic investment that will pay dividends

in improved health outcomes for all. From a policy implication perspective, solar energy for rural and remote healthcare specifically at the primary healthcare and sub-centre will promote effective healthcare outcomes with improved quality of services. Policy imperatives through National solar missions across LMICs should prioritise healthcare electrification through solar energy interventions that will lead to direct and indirect impact through improved healthcare services realising the aspect of healthcare for all – UHC and at the same time making solar energy as a part of healthcare planning for rural and remote healthcare electrification.

Ethical Consideration

The study is based on secondary data collected from published sources such as journal articles, reports and policy documents with no primary data and no human participants involved. All sources of information have been properly cited and acknowledged.

Data Availability

This paper uses data from published articles and existing policy papers which is already available in public domain. The detailed information is already provided in the manuscript.

Conflict of Interest

The authors declare that they have no competing interests.

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Author Contributions

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