

Power Supply and Ultrasound Functionality in Malawi: Findings from the 2019 Harmonized
Health Facility Assessment (HHFA) Census Survey

Luyanda Ngongoma

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Committee:

Yanfang Su

Bryan Weiner

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Luyanda Z Ngongoma

University of Washington

Abstract

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Assessment (HHFA) Census Survey

Luyanda Ngongoma

Chair of the Supervisory Committee:

Yanfang Su

Department of Global Health

This study examines the association between power supply and the availability and functionality of ultrasound (USS) equipment in Malawi's healthcare facilities, using data from the 2019 Harmonized Health Facility Assessment (HHFA). A cross-sectional design was utilized, analyzing 1,052 facilities across Malawi's three-tiered healthcare system. Key variables included power access, reliability, usage, and generator availability, with statistical models adjusted for facility level, ownership, and geographic location. The results show a significant association between complete power access and higher odds of functional USS equipment. Facilities with complete power access had over eight times higher odds of functional USS equipment (OR = 8.26, CI 3.58 - 19.04, $p < 0.001$) than those without power access. Partial power access was associated with lower odds of functional USS equipment (OR = 0.13, CI 0.056 - 0.319, $p < 0.001$). Facilities that used electricity specifically for medical devices had higher odds of functional USS equipment (OR = 2.83, $p < 0.001$). Power reliability was also crucial; facilities with fewer than 2 hours of power interruptions per day had higher odds of functional USS (OR = 1.97, $p < 0.001$). However, generator availability showed a less consistent association, with facilities having generators being less likely to have functional USS equipment (OR = 0.42, $p = 0.009$). Disparities were observed across facility levels, regions, and ownership types, with secondary and rural facilities showing superior USS functionality compared to primary and urban facilities. Christian Health Association of Malawi (CHAM) and NGO-owned facilities outperformed government-owned facilities in equipment functionality, with CHAM facilities showing 58.9% functional USS compared to 46.4% in government facilities. The study highlights the potential of handheld point-of-care ultrasound (HPOCUS) devices to address power-related constraints, offering a promising solution for resource-limited settings. However, the cross-sectional nature of the data limits causal

inferences, and future research should consider additional contextual factors such as workforce and financing. Overall, targeted investments in power infrastructure and innovative diagnostic technologies are essential for improving healthcare delivery in Malawi and similar low-resource settings.

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ACRONYMS

WHO: World Health Organization

USS: Ultrasound

LMIC: Low-to-Middle Income Countries

POCUS: Point-of-Care Ultrasound

HPOCUS: Handheld Point-of-Care Ultrasound

OR4C: Organizational Readiness for Change

DALY: Disability-Adjusted Life Year

CHAM: Christian Health Association of Malawi

SARA: Service Availability and Readiness Assessment

MFL: Master Facility List

MICE: Multiple Imputation by Chained Equations

HHFA: Harmonized Health Facility Assessment

AIM

To use Malawi's 2019 Harmonized Health Facility Assessment (HHFA) survey to evaluate the association of electricity supply on ultrasound (USS) availability and functionality in Malawi's healthcare facilities.

Objectives

1. Describe USS availability and functionality across Malawi's healthcare facilities (publicly and privately funded)
 - Use x-ray availability and functionality as a comparative control (another essential basic diagnostic innovation) for the USS findings.
 - Conduct a brief gap analysis between USS availability and functionality across Malawi's three-tiered healthcare system
2. Investigate the association between electricity supply and USS availability and functionality

INTRODUCTION

Recommended by the World Health Organization (WHO) as an essential imaging tool during the pandemic, ultrasound (USS) remains a constrained innovation in low-to-middle-income countries (LMIC)(1,2). Critical elements needed to achieve USS service delivery include equipment with diverse imaging operational capabilities; electricity (both battery and alternating current (AC) power sources); human resources (e.g. training and expertise) and adherence to international standards to guarantee safe and reliable usage in varied clinical environments(2). Flessa and Huebner (3) define healthcare innovations like USS as "sources of any improvement in the quality of services and quality of life". Similarly, Weiner(4) refers to such improvements as "collective behaviour changes" ranging from staffing to process management and these work in tandem to achieve readiness for change within organizations. To achieve change organizational readiness for change (OR4C), Weiner (4) posits a framework that prioritizes contextual factors as the initial step, highlighting organizational resources such as power supply among four other factors. Referred to as "the golden thread" (5) that cross-cuts many sustainable development goals (SDGs), the power supply is essential in the delivery of quality healthcare. Thus ranking modestly on the Global Innovation Index for Healthcare (118 out of 129) and with a documented history of national power grid constraints, Malawi is

ideal in assessing the relationship between electricity supply and USS delivery that is implemented across the country's three-tiered healthcare system (6).

Ultrasound as an Innovative Technology

USS is a non-ionizing, non-invasive imaging modality with diverse indications across a variety of clinical disciplines(1,7,8). More notably, its applications within antenatal care are crucial in the delivery of quality healthcare, particularly in Malawi where maternal and neonatal causes were the leading contributors of DALYs in 2019 (9). USS equipment is traditionally cart-based; these are larger machines mounted on wheeled carts, designed to be moved around within a healthcare facility but still reliant on stable, continuous power sources(10). However recent developments have achieved portability in various formats (10). These Portable USS options have helped clinicians render bedside USS assessments, commonly known as point-of-care-ultrasound (POCUS), to swiftly assess and address the patient's presenting complaints, instead of the more time-costly formal scanning and reporting done by technicians and radiologists (10). Handheld POCUS (HPOCUS) is characterized by a pocket-sized probe that is compatible with a variety of laptop and mobile operating systems (e.g. Windows, IOS)(11). Advantages of HPOCUS in resource-limited settings include increased diagnostic access allowing tele-consultation, affordability, portability, and reduced reliance on a stable power supply(10,11). These devices have demonstrated their reliability in diverse remote locales and the key to this is the ability to operate efficiently using battery power(12). Conversely, some drawbacks include poorer image resolution, absence of advanced imaging features, limited battery endurance, dependency on internet connectivity for data storage, and higher risk of loss and damage (10,11). To date, HPOCUS has been trialled in neighbouring geographies such as Tanzania and Kenya (13,14). This innovation, the workflow optimizations it offers, and its potential health outcome impacts are promising, especially as Malawi's radiology system faces challenges related to the severe shortage of trained human resources, inadequate infrastructure, and the frequent lack of essential equipment. These systemic issues underscore the potential of HPOCUS to significantly improve diagnostic services in resource-constrained environments.

Power Supply: An Organizational Resource

WHO estimates that 1 in 10 health facilities in Sub-Saharan Africa have limited access to a reliable electricity source(15). The power supply is needed in healthcare facilities for various essential services such as lighting, refrigeration of medical goods, operation of medical and diagnostic tools, and temperature control (16). The impacts of lack of power include jeopardized patient safety due to the inability to properly operate medical devices and sterilize equipment, interruptions in essential health services like emergency care and increased dependency on expensive and polluting diesel generators(16). Malawi's challenges are exacerbated by a dependence on hydropower, vulnerable to climate change which, (aside from an overloaded grid) has contributed to regular national blackouts - the worst of which were experienced in 2017 (17). Malawi's Ministry of Natural Resources, Energy, and Mining even considered importing coal power to meet the national shortfall despite this option's conflict with global trends towards sustainable renewable solutions(17).

OR4C and the Role of Resource

The OR4C framework introduces key concepts such as *change commitment* and *change efficacy* as key concepts(4). Organizational resources are defined as "the extent to which an organization has or can obtain the resources necessary to implement change" (4). Aside from infrastructural resources, the framework identifies "human, financial, material, and informational" (4) as other resource types whose their individual and shared impact on organizational readiness for change is nuanced. Furthermore, these resources are gain legitimacy through recognition by political, professional, economic, and cultural authorities (18).

It is hypothesized the functionality and availability of USS services in Malawi are interixably linked to issues of power supply. This thesis aims to describe this complex relationship within the Malawian healthcare context using the OR4C framework as a foundational resource and to briefly explore the suitability of handheld USS an emerging innovation that may help mitigate current power supply resource constraints.

METHODS

Study Design

A cross-sectional study design was chosen to assess the association between power supply and the readiness (availability and functionality) of USS services at the time of data collection.

Setting

Malawi's healthcare facilities are sub-divided according to their funding: public, private non-profit (PNP), and private-for-profit (PFP), with the latter two representing a smaller segment of the healthcare system (6,19). This study will describe USS readiness in public and privately funded healthcare facilities. Both government and Christian Health Association of Malawi (CHAM) facilities will be referred to as publicly funded since CHAM-managed facilities offer user-free services in partnership with the government and are the backbone of healthcare in Malawi's rural regions (6,19). The Malawian healthcare system is structured as a three-tiered referral pyramid, with escalating functional and resource capacity at each level (6,19). Health centers and rural community hospitals provide primary care services, district hospitals constitute the secondary level and the final tier consists of central hospitals (6,19). In terms of policy, the Malawian government's Health Sector Strategic Plan II (2017 - 2022), aimed to ensure that by the end of 2022, healthcare facilities maintained a 90% operational rate for electricity and that medical equipment appropriately available at each level of care would be functional on 90% of days annually(20).

Sampling

The Malawi 2019 Harmonized Health Facility Assessment (HHFA) employed a census strategy, aiming to collect data from all health facilities listed in the Malawi Master Facility List (MFL)(21). Of the 1224 facilities identified in the MFL, data was successfully collected from 1106. After accounting for missingness, a final sample of 1052 facilities were included in this analysis.

Measurement

The primary data source for this study was the Malawi 2019 HHFA, an optimized version of the Service Availability and Readiness Assessment (SARA) survey. Conducted from November 2018 to March 2019,

the Ministry of Health and Population, in collaboration with CHAM and district health officers, oversaw the survey implementation, including unannounced visits to ensure data accuracy and reliability(21).

The HHFA tool consists of five modules, and this thesis will focus on module 1, which assesses facility resources. Data collection was collected utilizing Survey Solutions Software installed on fieldworker electronic tablets. Multiple rounds of review were completed as the survey as the data passed through to data managers at the central level(21).

Variables

Independent Variables:

Power Access: Categorized based on the presence of main power and backup sources. Facilities were classified as having absent power (no main or backup power), partial power (main or alternative sources without secondary backup power), or complete power (main power and/or alternative sources with secondary backup power). Sub-dimensions of power access were:

- Power Reliability: Measured by the availability of electricity from the main or backup source during the facility's operating hours, categorized as always available (no interruptions), often available (interruptions of less than 2 hours per day), or sometimes available (frequent or prolonged interruptions).
- Usage: Defined by the purpose of electricity usage in the facility, including stand-alone electric medical devices/appliances, electric lighting and communications, or a combination of these uses.
- Generator Availability: Whether the facility had a generator available (Yes/No).

Dependent Variables:

In this study, device 'availability' is defined as the physical presence of ultrasound equipment within a facility. 'Functionality' is defined as the device being in working order and operational during the survey (reported).

Statistical Analysis

Missing data was addressed using the MICE package in R. Remaining outcome variables with missingness were excluded from the analysis. Chi-square or Fisher exact tests were used to test associations, with a significance level set at $p < 0.05$. Logistic regression models were employed to examine the association between power access, its sub-dimensions (usage, reliability, generator availability) and the availability and functionality of ultrasound (USS) in Malawian healthcare facilities. The models were adjusted for potential confounders, including geographical location (urban vs. rural), facility level (primary, secondary, tertiary), managing authority, and facility type. The general logistic regression model used was:

$$\text{logit}(\gamma_j) = \beta_0 + \beta_1 \text{energy type}_j + \beta_2 \text{facility level}_j + \beta_3 \text{managing authority}_j + \beta_4 \text{geography}_j + \varepsilon_j$$

Where:

γ_j represents the binary outcome (0 or 1) for facility j , indicating whether the diagnostic device (USS or X-ray) is functional.

β_1 : Energy type (characteristics of electricity supply)

β_2 : Facility levels (primary, secondary, tertiary)

β_3 : Managing authority (government, CHAM, private)

β_4 : Geography (urban/rural)

Due to perfect separation causing convergence issues, facility age was excluded from all models, and facility type was excluded from the generator models for both USS and X-ray. All statistical analyses were performed using RStudio version 2022.07.1+554.

RESULTS

Descriptive Statistics

After adjusting for missingness, 1052 of the 1106 facilities surveyed were included and ranged from primary (n= 964), secondary (n= 81) and tertiary (n= 7) level facilities (Table 1, Table 2).

Descriptive statistics identified findings related to geography, facility level and ownership and these factors would demonstrate relevance in statistical analysis.

USS services are universally available across all regions in Malawi, however interesting geo-regional patterns in availability and functionality are evident when devices are compared. The greater frequency of facilities in rural regions (n=763) alludes to a strong referral system with USS functionality performing better in rural areas (46.0%) compared to x-ray functionality which fares better in urban regions. Secondary facilities demonstrate the highest functionality for both devices (USS 85.2; X-ray 80.2%), outperforming primary-level facilities (USS at 40.8%; X-ray at 36.0%). These findings are further supported by the facility-level gap analysis (Table 3, appendix) which describes primary facilities as having the largest available functional gap. Hospital facilities have a higher proportion of device functionality for both devices (USS 83.0%; X-ray 78.0%), with clinic and health center facilities having more moderate device functionality. Interestingly, of the total facilities classified as new (10.5% of the total facilities), majority had USS and x-ray equipment available, however, there was a sharp decline in device functionality. For example, USS functionality at new facilities was 0%. Ownership is another factor that impacts device availability and functionality. Despite high availability, government-owned facilities report lower functionality for both USS (46.4%) and X-ray (37.5%). In contrast, CHAM and NGO-owned facilities perform better, particularly in USS functionality (CHAM 58.9%; NGOs 54.9%).

Figure 1 illustrates that most primary-level facilities (57.78%) have partial power access and only 35.37% have complete power access. Secondary facilities exhibit robust power access, with 96.30% benefiting from combination power sources. Interestingly, despite tertiary hospitals having more sophisticated resource demands, 28.57% of them operate with only partial power access. Further analysis reveals a strong dependence on the national grid as the primary power source across all three facility levels. Efforts to incorporate renewable energy sources, such as solar energy, are evident, particularly at the primary and

tertiary levels. However, this effort is offset by generators being a popular choice for backup power sources across these facilities (Figures 3, Appendix).

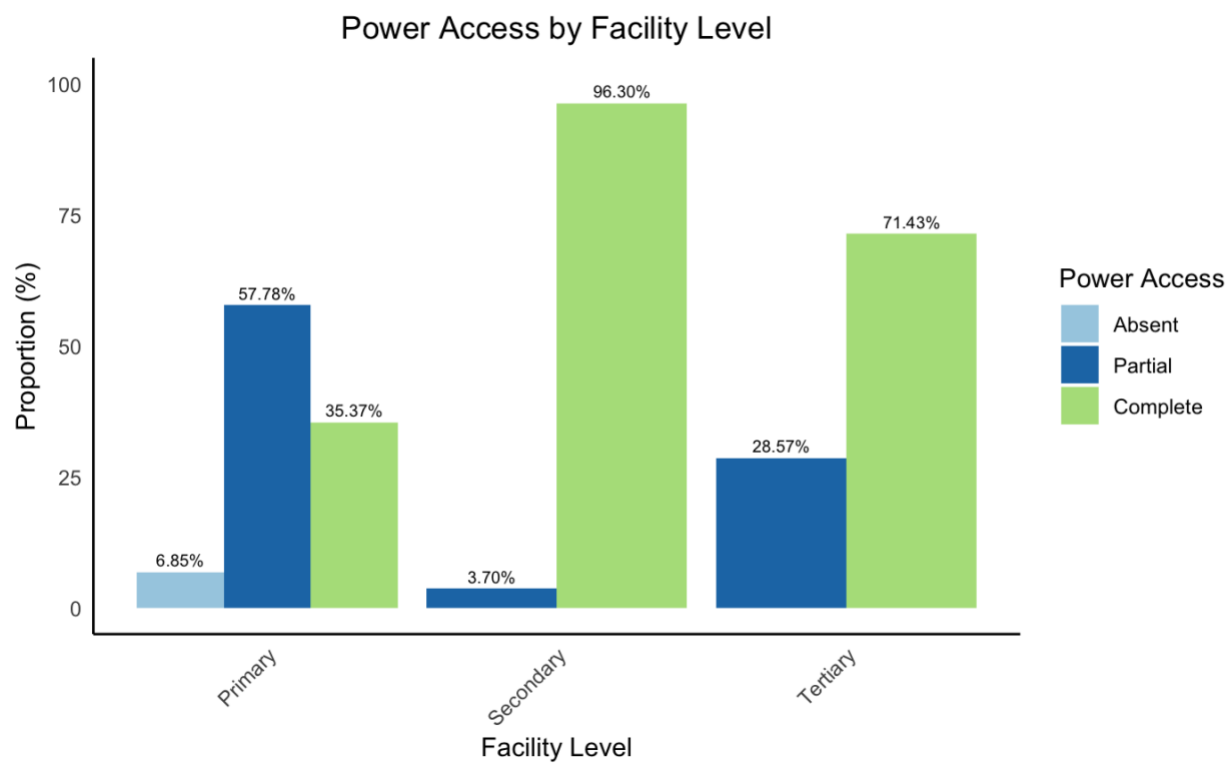


Figure 1 Power Accessibility by Facility Level

Table 1 Device Availability

Characteristic	Overall (N=1052, 100%)	Ultrasound	X-ray
		Yes (N=1052)	Yes (N=559)
Region			
Center	380	380 (100%)	191 (50.3%)
North	196	196 (100%)	83 (42.3%)
South	476	476 (100%)	285 (59.9%)
Geographical Area			
Rural	763	763 (100%)	375 (49.1%)
Urban	289	289 (100%)	184 (63.7%)
Facility Level			
Primary	964	964 (100%)	476 (49.4%)
Secondary	81	81 (100%)	77 (95.1%)
Tertiary	7	7 (100%)	6 (85.7%)
Facility Type			
Clinic	342	342 (100%)	201 (58.8%)
Dispensary	60	60 (100%)	24 (40.0%)
Health Centre	455	455 (100%)	228 (50.1%)
Health Post	95	95 (100%)	16 (16.8%)
Hospital	100	100 (100%)	90 (90.0%)
Facility Ownership			
CHAM	151	151 (100%)	87 (57.6%)
Government	560	560 (100%)	265 (47.3%)
NGO	51	51 (100%)	31 (60.8%)
Other (Specify)	23	23 (100%)	17 (73.9%)
Private	267	267 (100%)	159 (59.6%)
Facility Age			
No	942	942 (100%)	466 (49.5%)
Yes	110	110 (100%)	93 (84.5%)
Availability of Antenatal Care			
No	425	425 (100%)	196 (46.1%)
Yes	627	627 (100%)	363 (57.9%)
Power access			
Absent	66	66 (100%)	23 (34.8%)
Partial	562	562 (100%)	145 (25.8%)
Complete	424	424 (100%)	391 (92.2%)
Availability of Main Electricity Source			
No	123	123 (100%)	53 (43.1%)
Yes	929	929 (100%)	506 (54.5%)
Availability of Secondary Electricity Source			
No	605	605 (100%)	150 (24.8%)
Yes	447	447 (100%)	409 (91.5%)
Availability of Generator			
No	884	884 (100%)	398 (45.0%)
Yes	164	164 (100%)	158 (96.3%)
Missing	4	4 (100%)	3 (75.0%)
Reliability of Electricity Source in Last 7 Days			
Always Available	400	400 (100%)	220 (55.0%)
Often Available	270	270 (100%)	116 (43.0%)
Sometimes Available	382	382 (100%)	223 (58.4%)
Electricity Usage Towards Medical Devices			
No	216	216 (100%)	94 (43.5%)
Yes	836	836 (100%)	465 (55.6%)

Table 2 Device Functionality

Characteristic	Overall (N=1052 100%)	Ultrasound		X-ray	
		No (N=586)	Yes (N=466)	No (N=635)	Yes (N=417)
Region					
Center	380	210 (55.3%)	170 (44.7%)	249 (65.5%)	131 (34.5%)
North	196	100 (51.0%)	96 (49.0%)	142 (72.4%)	54 (27.6%)
South	476	276 (58.0%)	200 (42.0%)	244 (51.3%)	232 (48.7%)
Geographical Area					
Rural	763	412 (54.0%)	351 (46.0%)	471 (61.7%)	292 (38.3%)
Urban	289	174 (60.2%)	115 (39.8%)	164 (56.7%)	125 (43.3%)
Facility Level					
Primary	964	571 (59.2%)	393 (40.8%)	617 (64.0%)	347 (36.0%)
Secondary	81	12 (14.8%)	69 (85.2%)	16 (19.8%)	65 (80.2%)
Tertiary	7	3 (42.9%)	4 (57.1%)	2 (28.6%)	5 (71.4%)
Facility Type					
Clinic	342	230 (67.3%)	112 (32.7%)	220 (64.3%)	122 (35.7%)
Dispensary	60	30 (50.0%)	30 (50.0%)	41 (68.3%)	19 (31.7%)
Health Centre	455	239 (52.5%)	216 (47.5%)	270 (59.3%)	185 (40.7%)
Health Post	95	70 (73.7%)	25 (26.3%)	82 (86.3%)	13 (13.7%)
Hospital	100	17 (17.0%)	83 (83.0%)	22 (22.0%)	78 (78.0%)
Facility Ownership					
CHAM	151	62 (41.1%)	89 (58.9%)	76 (50.3%)	75 (49.7%)
Government	560	300 (53.6%)	260 (46.4%)	350 (62.5%)	210 (37.5%)
NGO	51	23 (45.1%)	28 (54.9%)	22 (43.1%)	29 (56.9%)
Other (Specify)	23	10 (43.5%)	13 (56.5%)	10 (43.5%)	13 (56.5%)
Private	267	191 (71.5%)	76 (28.5%)	177 (66.3%)	90 (33.7%)
Facility Age					
No	942	476 (50.5%)	466 (49.5%)	567 (60.2%)	375 (39.8%)
Yes	110	110 (100.0%)	0 (0.0%)	68 (61.8%)	42 (38.2%)
Availability of Antenatal Care					
No	425	299 (70.4%)	126 (29.6%)	300 (70.6%)	125 (29.4%)
Yes	627	287 (45.8%)	340 (54.2%)	335 (53.4%)	292 (46.6%)
Power access					
Absent	66	39 (59.1%)	27 (40.9%)	48 (72.7%)	18 (27.3%)
Partial	562	489 (87.0%)	73 (13.0%)	497 (88.4%)	65 (11.6%)
Complete	424	58 (13.7%)	366 (86.3%)	90 (21.2%)	334 (78.8%)
Availability of Main Electricity Source					
No	123	73 (59.3%)	50 (40.7%)	85 (69.1%)	38 (30.9%)
Yes	929	513 (55.2%)	416 (44.8%)	550 (59.2%)	379 (40.8%)
Availability of Secondary Electricity Source					
No	605	526 (86.9%)	79 (13.1%)	536 (88.6%)	69 (11.4%)
Yes	447	60 (13.4%)	387 (86.6%)	99 (22.1%)	348 (77.9%)
Availability of Generator					
No	884	541 (61.2%)	343 (38.8%)	596 (67.4%)	288 (32.6%)
Yes	164	45 (27.4%)	119 (72.6%)	38 (23.2%)	126 (76.8%)
Missing	4	0 (0.0%)	4 (100.0%)	1 (25.0%)	3 (75.0%)
Reliability of Electricity Source in Last 7 Days					
Always Available	400	243 (60.8%)	157 (39.2%)	252 (63.0%)	148 (37.0%)
Often Available	270	127 (47.0%)	143 (53.0%)	187 (69.3%)	83 (30.7%)
Sometimes Available	382	216 (56.5%)	166 (43.5%)	196 (51.3%)	186 (48.7%)
Electricity Usage Towards Medical Devices					
No	216	146 (67.6%)	70 (32.4%)	154 (71.3%)	62 (28.7%)
Yes	836	440 (52.6%)	396 (47.4%)	481 (57.5%)	355 (42.5%)

Main Outcome

The adjusted power access model (Figure 4a) revealed a significant association between power access, the availability of x-ray equipment and the functionality of both devices. Facilities with complete power access are significantly more likely to have functional USS equipment, with odds over eight times higher than those without power access (OR = 8.26, CI 3.58 - 19.04, p-value < 0.001). In contrast, facilities with partial power access show lower odds of having functional USS equipment (OR = 0.13, CI 0.056 - 0.319, p-value < 0.001) than facilities with absent power supply access. Similarly, both chi-tests for x-ray availability (X-squared 437.56, p-value < 2.2e-16) and functionality (X-squared 4.05 p-value = 0.04), confirmed a strong association with power access. Facilities with complete power access have significantly higher odds of having x-ray equipment available (OR = 4.09, p-value < 0.001) and functional (OR = 4.09, p-value < 0.002) than those with no power access. However, partial power access is associated with lower odds of availability (OR = 0.16, p-value < 0.001) and functionality (OR 0.13, p-value < 0.001) when compared to facilities with absent power access.

Facilities that dedicate electricity towards medical devices (Figure 4b) have higher odds of x-ray availability (OR = 1.80, p-value = 0.014) and device functionality (USS odds ratio 2.83, p-value = 0.0002; X-ray odds ratio 2.00, p-value = 0.009). Chi-square analysis across these three outcomes demonstrated a positive association with significant p-values. The investigation into Generator availability showed little similarities between the devices (Figure 4d). A significant chi-squared association was present only for the x-ray availability outcome (X-squared = 10.30, p-value = 0.001) and logistic regression findings were only observed in the adjusted USS functionality ((OR = 0.42, p-value = 0.009) and x-ray availability (OR = 1.65, p-value = 0.006428) models. The analysis of power reliability shows significant associations with the functionality and availability of both USS and X-ray equipment. For USS functionality, facilities with power interruptions of less than 2 hours per day have higher odds of functionality compared to those with no interruptions (OR = 1.97, p-value < 0.001). Analysis of X-ray availability shows facilities with frequent interruptions have lower odds compared to those with reliable power (OR = 0.63 p-value = 0.011). X-ray functionality shows frequent power interruptions have higher odds of functionality compared to those with reliable power (OR = 1.67, p-value = 0.002).

Other Analyses

Facilities offering antenatal care have significantly higher odds of having functional USS equipment compared to those that do not (OR = 2.28, p-value < 0.001) and this is further highlighted by the chi-squared test confirming a significant association between antenatal care availability and USS functionality (X-squared = 61.03, p-value = 5.63e-15).

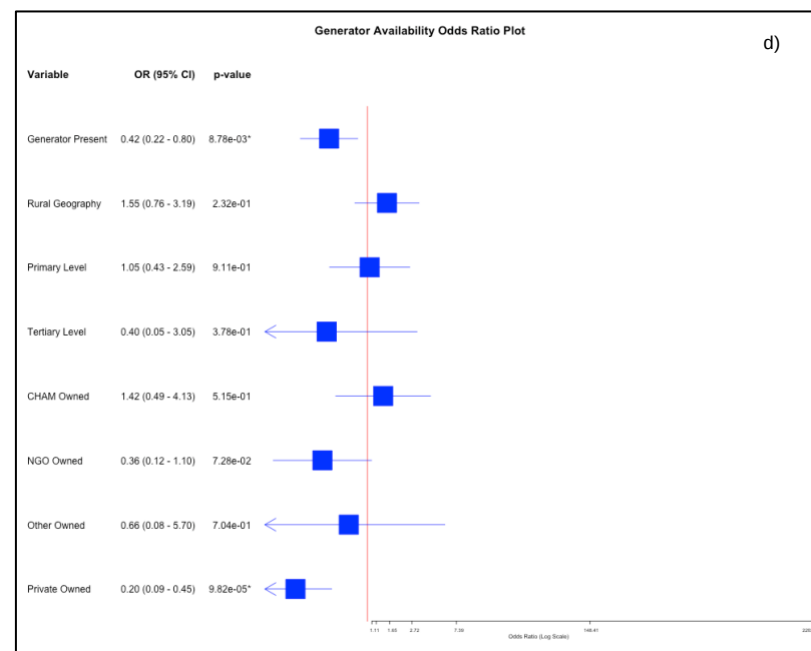
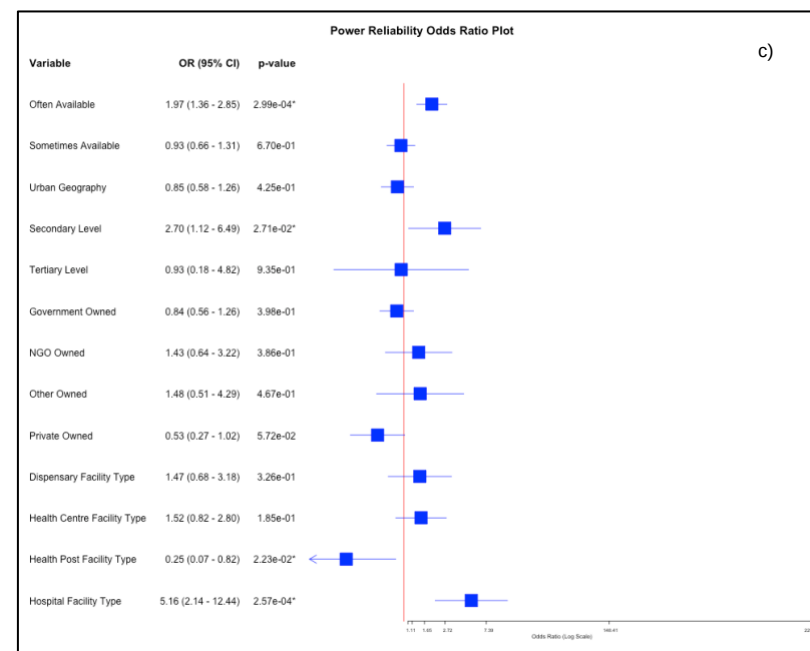
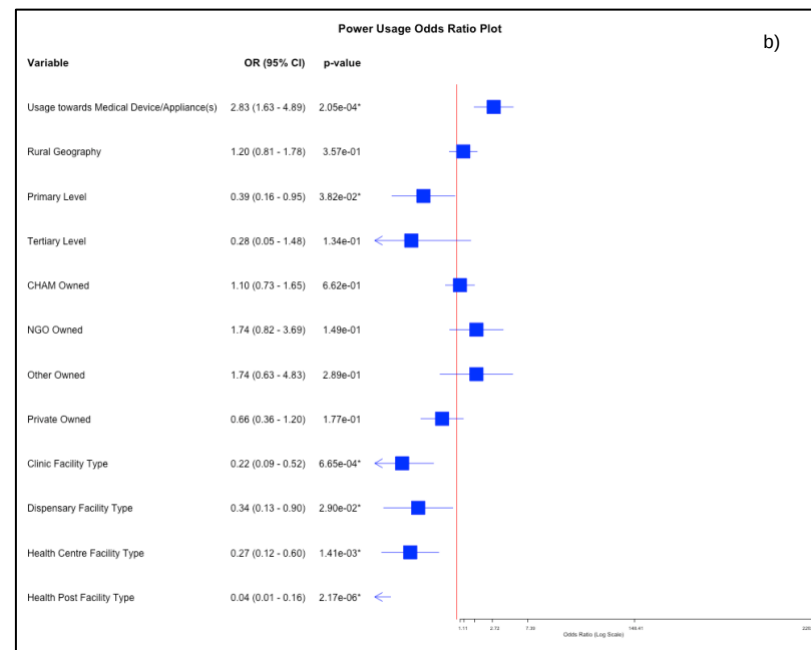
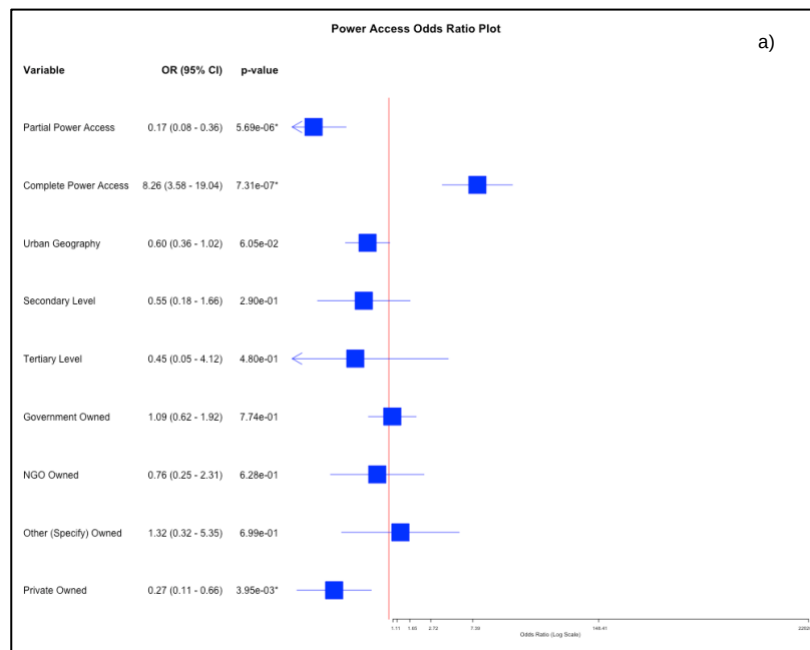


Figure 4: Odds Ratio Plots for Power Access, Power Usage, Power Reliability, and Generator Availability in Malawian Healthcare Facilities. Asterisks (*) indicates p-value significance

DISCUSSION

Key Results

This study aimed to evaluate the association between electricity supply and ultrasound (USS) availability and functionality in Malawi's healthcare facilities, using the OR4C conceptual framework as a foundational guide. The descriptive and statistical results identified three critical covariables: regional, facility level, and ownership. Geo-regional analysis reveals USS is universally available across all regions in Malawi however, device functionality varies. In rural areas, USS functionality is superior compared to urban areas and in contrast, X-ray functionality is higher in urban regions. This could be explained by differing donor funding priorities (focusing on essential services like antenatal care) and urban areas benefitting from better infrastructure, a higher workforce concentration and more diverse funding sources for maintaining advanced diagnostic equipment. Frija et al(22) emphasize this need for targeted improvements in rural regions and present innovations such as portable diagnostic devices (USS and X-ray) and artificial intelligence (AI) as key tools to enhance medical imaging in LMICs. The primary level of care has the highest proportion of facilities with absent power access and the lowest proportion of facilities with complete power access. Research(23) demonstrates that a combination power supply at the facility level protects expensive imaging equipment from damage and improves imaging reliability. Our results support this as secondary facilities with better power access, demonstrate the highest functionality for both USS and X-ray. Furthermore, ownership significantly impacts the functionality of diagnostic equipment. Malawi's 2013-2014 Service Provision Assessment (SPA)(24) showed CHAM facilities performed best regarding X-ray and USS diagnostic capacity, with the government following suit. Our findings conflict with previous findings as while CHAM facilities continue to perform well, government-owned facilities report lower functionality for both USS and X-ray, indicating better management and resource allocation practices in non-governmental facilities and the importance of such facilities in providing basic diagnostic imaging for the population.

Power access is significantly associated with the functionality of both USS and X-ray equipment. Facilities with complete power access have markedly higher odds of functional USS and X-ray equipment compared to those without power. Conversely, facilities with partial power access showed significantly lower odds of functional USS equipment. Additionally, the analysis also indicates a significant relationship between the

usage of electricity for medical devices and the functionality and availability of diagnostic equipment. Moreover, generator availability shows no significant chi-squared association with USS functionality and facilities with generators have lower odds of functional ultrasound equipment. For X-ray functionality, however, facilities with generators are more likely to have functional ultrasound equipment, highlighting the importance of reliable backup power sources. Power reliability is significantly associated with both USS and X-ray functionality and availability. Facilities with power interruptions of less than two hours per day have higher odds of functional USS compared to those with no interruptions.

Other associations explored were antenatal care services and ultrasound. These results showed a significant association with USS functionality. Facilities offering antenatal care have significantly higher odds of having functional USS equipment, highlighting the importance of integrating diagnostic services with maternal health care.

Limitations

This study has several limitations. The cross-sectional nature of the data limits the ability to draw causal inferences. Additionally, the dataset is from the 2019 survey, which may affect the current relevance of the findings in their usage towards country implementation. The results do not account for key OR4C contextual factors such as workforce, financing etc. Furthermore, seasonal variations in power supply and the specific characteristics of backup power sources and USS types (portable, handheld etc) were not captured, potentially impacting the generalizability of the findings.

Interpretation

Overall, x-rays served as a valuable comparative control for evaluating the impact of electricity on diagnostic service functionality. The similar trends in the association between power access and the functionality of both USS and x-ray equipment reinforce the critical role of stable electricity in maintaining diagnostic capabilities. However, the slightly higher functionality of X-rays in urban areas compared to USS highlights potential differences in infrastructural support and usage patterns between the two diagnostic tools. This suggests that while both tools benefit from good power supply access, x-ray equipment might be more

sensitive to variations in power quality and infrastructure support, potentially due to its higher power requirements and more complex maintenance needs.

The phenomenon where facilities with partial power access show lower odds of having functional USS equipment compared to those with absent power supply access, while facilities with complete power access have significantly higher odds of functional USS equipment, can potentially be explained by several factors. Partial power access often implies reliance on a single, unstable power source without backup, leading to frequent interruptions detrimental to sensitive equipment. Facilities with absent power might avoid the pitfalls of unreliable power by using non-electrical alternatives, such as handheld battery-operated USS devices, or minimal equipment, which could paradoxically result in better-reported functionality. Complete power access facilities benefit from stable, continuous power, allowing regular maintenance and reliable operation of USS equipment. In contrast, partial power access facilities face more frequent power fluctuations, preventing proper maintenance and degrading equipment reliability. This overdependence on an unstable power source results in frequent service disruptions, impacting equipment functionality.

This study found that the availability and functionality of USS and x-ray equipment in healthcare facilities are significantly influenced by power access and its reliability. The OR4C framework highlights the importance of resource availability, and this is echoed in the results(4). In rural areas, targeted funding and support programs have likely enhanced USS outcomes. Similarly, the robust power access in urban regions further supports the outcomes positively. The framework also highlights the importance of understanding task demands and situational factors(4). In rural areas, the focus on primary healthcare services means that the demand for functional ultrasound equipment is high, aligning with the task demands of these settings. Conversely, urban healthcare facilities, which often serve as referral centers, have more complex task demands that necessitate the availability and functionality of x-ray equipment. These facilities are better equipped to handle the technical and logistical requirements of maintaining such basic diagnostic tools due to their access to specialized staff and better resource allocation.

Generalizability

While the study focuses on Malawi, the findings may have broader implications for other low-resource settings facing similar challenges with power infrastructure and diagnostic service delivery. Future research should explore the influence of other OR4C contextual factors on the relationship between power supply and basic diagnostic device outcomes as this will allow for holistic feasibility studies on innovative handheld USS solutions.

CONCLUSION

This study highlights the crucial role of reliable power supply in the availability and functionality of ultrasound (USS) and X-ray equipment in Malawi's healthcare facilities. Facilities with complete power access show significantly higher odds of functional diagnostic equipment, underscoring the importance of stable electricity. Disparities in equipment functionality across facility levels, regions, and ownership types emphasize the need for effective resource management. The potential of handheld point-of-care ultrasound (HPOCUS) devices, which are less dependent on stable power, presents a promising solution for resource-limited settings. Overall, targeted investments in power infrastructure and innovative diagnostic technologies are essential for improving healthcare delivery in Malawi.

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APPENDIX

Table 3 Device Gap Analysis by Facility Level

Facility Level	Ultrasound			X-ray		
	Available (N=1052)	Functional (N=466)	Gap (N=586)	Availability (N=559)	Functional (N=417)	Gap (N=142)
Primary	964	393	571 (59.2%)	476	347	129 (27.1%)
Secondary	81	69	12 (14.8%)	77	65	12 (15.6%)
Tertiary	7	4	3 (42.9%)	6	5	1 (16.7%)

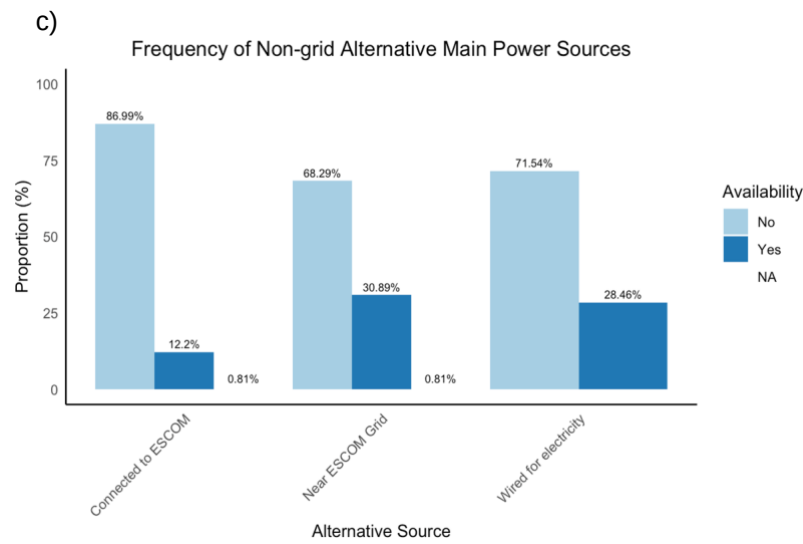
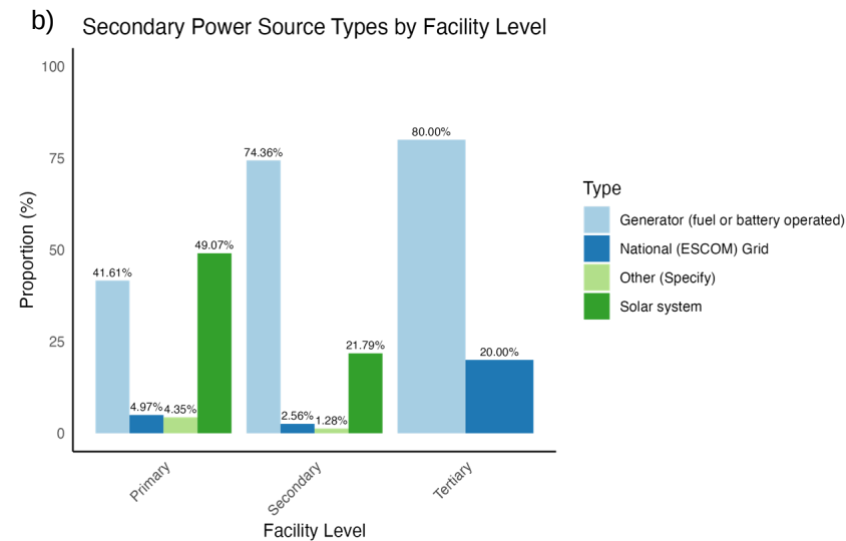
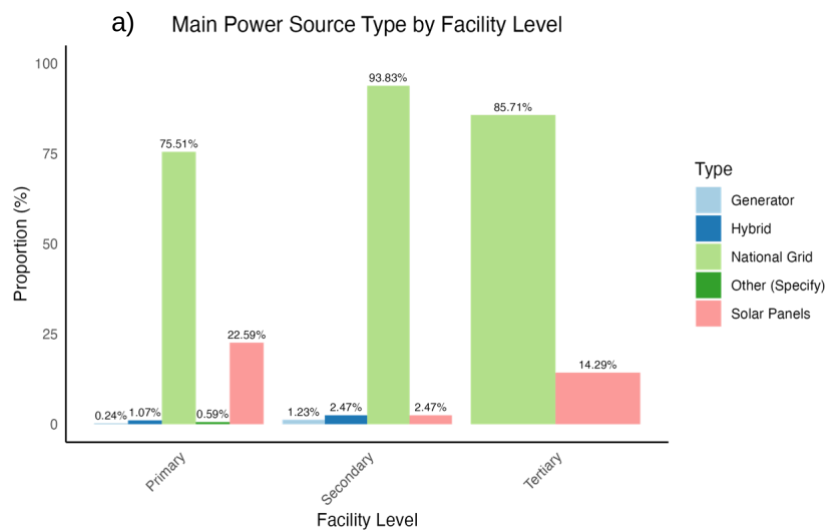


Figure 3: Analysis of Power Source Types and Availability Across Healthcare Facility Levels

- (a) Proportion of Main Power Source Types by Facility Level
- (b) Proportion of Secondary Power Source Types by Facility Level
- (c) Frequency of Non-grid Alternative Main Power Sources