

UNIVERSITY OF GENOVA



**Università
di Genova**

Master's degree in engineering technology for Strategy and Security

**ANALYSIS OF ENERGY REQUIREMENTS AND PRELIMINARY STUDY FOR
THE IMPLEMENTATION OF PHOTOVOLTAIC SYSTEMS IN KENYAN
HOSPITALS**

*Comparative study of seven faith-based hospitals, with Our Lady of Lourdes Rangala
Mission Hospital (Project 1004) as the detailed reference case*

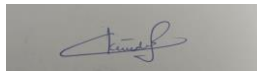
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DECLARATION

I declare that this thesis is an original synthesis of the work carried out during my internship at SEVA 4 AFRICA and of the subsequent academic analysis. Project spreadsheets, drawings, quotations and communications supplied for the study have been used as primary project evidence. External technical and institutional sources are acknowledged in the reference list. Where project information was incomplete, the thesis identifies assumptions and recommends verification before procurement or construction.

Signature:

A rectangular box containing a handwritten signature in blue ink. The signature is cursive and appears to be 'T. M. F.'.

Date: 05/10/2026

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I would like to express my sincere gratitude to the University of Genova and to the teaching staff of the master's degree in engineering technology for Strategy and Security for the academic knowledge, guidance, and interdisciplinary perspective provided throughout my studies. The program offered a valuable opportunity to approach engineering not only from a technical perspective, but also in relation to strategy, security, management, and the broader social and operational contexts in which engineering solutions are implemented.

I am particularly grateful to my academic supervisor for the guidance, constructive feedback, and support provided during the development of this thesis. Their advice and academic perspective were valuable in shaping the structure of the research, refining its objectives, and maintaining a clear connection between the technical analysis and the broader strategic considerations addressed in this work.

I would also like to extend my sincere appreciation to the SEVA 4 AFRICA team for providing me with the opportunity to undertake the internship that contributed substantially to the development of this thesis. The experience provided a valuable practical context in which to connect the concepts developed during the master's program with real operational challenges. In particular, the internship allowed me to explore the interconnections between energy engineering, strategic planning, procurement, risk management, and social impact. This interdisciplinary experience was fundamental in understanding how technical decisions can influence operational continuity, resource efficiency, and the delivery of essential services in challenging contexts.

Finally, I would like to acknowledge everyone who, directly or indirectly, contributed to the completion of this work. The combination of academic guidance, practical experience, institutional cooperation, and access to operational information has been instrumental in bringing this thesis to completion. I am sincerely grateful to all those who supported this process and contributed to making this research possible.

ABSTRACT

Reliable electricity is essential for safe and continuous healthcare delivery. This thesis develops and demonstrates a transparent preliminary methodology for assessing photovoltaic (PV) and battery-energy-storage-system (BESS) opportunities in healthcare facilities using incomplete and heterogeneous field information. The study examines seven faith-based hospitals in western Kenya, with Our Lady of Lourdes Rangala Mission Hospital serving as the detailed reference case.

Data was obtained from structured questionnaires, electricity bills, generator records, equipment inventories, geographic information, PVGIS outputs and preliminary engineering and procurement documents. The methodology combines portfolio-level screening with detailed case-study analysis and explicitly distinguishes observed data, derived values and engineering assumptions.

For Rangala, the available 2025 billing information indicates average grid electricity consumption of approximately 50.36 kWh/day. Recorded generator fuel corresponds to approximately 0.37 kWh/day using the project's preliminary conversion factor, giving a combined screening estimate of approximately 50.73 kWh/day. The reported photovoltaic specific productivity is 1,573.98 kWh/kWp/year, resulting in a preliminary energy-balance requirement of approximately 11.76–11.83 kWp. The latest project concept specifies twenty 620 W modules, corresponding to 12.4 kWp.

The study also identifies significant design-document inconsistencies, including alternative PV capacities, battery-storage capacities and inverter configurations. These differences demonstrate the importance of traceability and controlled reconciliation during preliminary engineering. Battery capacity is not finalized because a verified critical-load profile, outage history and autonomy requirement are not yet available.

The results indicate that the available evidence is sufficient to establish a preliminary engineering basis and justify progression to site survey and detailed design, but not to authorize construction. Final implementation requires verification of electrical loads, critical circuits, roof structure, shading, protection coordination, generator integration, battery autonomy, equipment compatibility, regulatory requirements and project cost.

The principal contribution of the thesis is a practical and traceable methodology for converting incomplete healthcare energy data into a defensible preliminary PV-BESS design

basis while explicitly identifying uncertainty and the additional evidence required for detailed engineering.

Keywords: photovoltaic systems; battery energy storage; healthcare energy; Kenya; PVGIS; energy assessment; resilience; preliminary design; data uncertainty; Rangala Mission Hospital.

SUMMARY

The thesis analyzes the energy needs of seven denominational hospitals in western Kenya and develops a preliminary study for the implementation of photovoltaic systems, taking Our Lady of Lourdes Rangala Mission Hospital as the main case. The analysis integrates questionnaires, utility bills, load inventories, generator data, geographical coordinates, PVGIS results and technical project files. For Rangala, an overall average consumption of about 50.73 kWh/day has been estimated. The specific producibility of 1,573.98 kWh/kWp/year leads to a preliminary energy size of about 11.83 kWp; the most recent configuration considers twenty 620 W modules, i.e. 12.4 kWp. The study highlights preliminary technical feasibility and identifies the necessary checks before the executive design and installation.

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LIST OF ACRONYMS/ ABBREVIATIONS

AC	Alternating Current
BESS	Battery Energy Storage System
BMS	Battery Management System
BMU	Battery Management Unit
BOM	Bill of Materials
CAPEX	Capital Expenditure
DC	Direct Current
DoD	Depth of Discharge
EMS	Energy Management System
EPRA	Energy and Petroleum Regulatory Authority
GHI	Global Horizontal Irradiation
IEC	International Electrotechnical Commission
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KSh	Kenyan Shilling
LCOE	Levelized Cost of Electricity
MLT	MLT Project S4A
MPPT	Maximum Power Point Tracker
NPV	Net Present Value
O&M	Operation and Maintenance
OPD	Outpatient Department
PR	Performance Ratio
PV	Photovoltaic

PVGIS	Photovoltaic Geographical Information System
PVPS	Photovoltaic Power Systems Programme
RFQ	Request for Quotation
RQ	Research Question
SEforALL	Sustainable Energy for All
SPD	Surge Protective Device
STC	Standard Test Conditions
UPS	Uninterruptible Power Supply
WHO	World Health Organization

LIST OF SYMBOL AND UNITS

A	Ampere
V	Volt
W	Watt
kW	Kilowatt
kWh	Kilowatt-hour
KWp	Kilowatt-peak
kVA	Kilovolt-ampere
MWh	Megawatt-hour
I_{sc}	Short-circuit current
V_{oc}	Open-circuit voltage

CHAPTER 1: INTRODUCTION

1.1 Background and motivation

Electricity in a hospital should be understood not simply as a conventional utility input, but as a fundamental clinical enabling service. The availability, quality, and continuity of electrical power directly influence the ability of healthcare facilities to deliver safe and effective medical services. Lighting is required for routine care, emergency procedures, and surgical activities; refrigeration and cold-chain systems are essential for the preservation of vaccines, medicines, blood products, and other temperature-sensitive materials; while sterilization equipment, laboratory systems, diagnostic devices, communications infrastructure, information systems, ventilation, and water-pumping systems all depend on an adequate electricity supply. Consequently, interruptions in electricity supply can have effects that extend well beyond inconvenience or loss of productivity. A short interruption may delay a medical procedure, interrupt diagnostic activities, affect the storage conditions of temperature-sensitive products, disrupt communications or digital records, and require healthcare personnel to rely on alternative procedures or backup equipment.

The relationship between energy and healthcare is particularly significant in low- and middle-income countries, where electricity infrastructure may be constrained by limited generation capacity, network reliability, geographical isolation, financial resources, or the high operating costs associated with backup generation. The World Health Organization (WHO), in collaboration with the World Bank, the International Renewable Energy Agency (IRENA), and Sustainable Energy for All (SEforALL), estimates that close to one billion people in low- and lower-middle-income countries are served by healthcare facilities with either unreliable electricity or no electricity access at all. In sub-Saharan Africa, approximately 15% of healthcare facilities have no electricity access, while only around 40% of healthcare facilities overall have reliable electricity; among hospitals specifically, only about half report reliable electricity access.

These figures demonstrate that the challenge is not limited to connecting healthcare facilities to an electrical network. The reliability and adequacy of the supply are equally important determinants of whether electricity can effectively support healthcare delivery.

This distinction between electricity access and electricity reliability is particularly relevant for hospitals. A facility may be formally connected to the national grid while still experiencing interruptions, voltage fluctuations, or other limitations that affect its operations. Moreover, electricity can represent a significant recurring operational cost, particularly when facilities must supplement grid electricity with diesel generators during outages. The resulting expenditure is not limited to fuel consumption. Backup generation also involves equipment acquisition, maintenance, replacement, fuel logistics, and operational management. These costs can place additional pressure on healthcare facilities whose financial resources are already directed toward personnel, medicines, medical equipment, and patient services. IRENA has therefore highlighted the importance of considering both capital and recurring energy costs, including operation and maintenance requirements, when planning energy solutions for healthcare facilities.

The energy challenge also has a spatial and operational dimension. Rural and remote healthcare facilities generally face greater difficulties in obtaining reliable electricity than facilities located in urban areas. Even where grid infrastructure is available, the quality and continuity of supply may not be sufficient to guarantee uninterrupted operation of essential services. This creates a particular vulnerability for facilities that cannot simply suspend operations during an outage. A hospital must continue to provide essential services regardless of whether the external electricity network is functioning normally. Consequently, energy planning for healthcare requires consideration not only of the quantity of electricity consumed, but also of when electricity is required, which loads are critical, how long interruptions can be tolerated, and what alternative sources are available when the primary supply fails. WHO identifies reliable electricity as an important enabler of essential healthcare services, including safe childbirth, immunization, diagnostics, emergency response, communications, and access to clean water.

Within this context, distributed renewable energy systems have emerged as a potential means of improving both the sustainability and resilience of healthcare electricity supply. Solar photovoltaic (PV) systems are particularly relevant because they can be deployed at or close to the point of consumption and can generate electricity without the fuel requirements associated with conventional backup generators. Depending on system configuration, a PV installation can supply part of a facility's daytime electricity demand directly, reducing the amount of electricity imported from the grid. When combined with battery energy storage, the system can also store surplus solar generation and make it available at later times,

including periods when solar production is unavailable or when the grid supply is interrupted. Such systems can therefore be designed not only as energy-cost reduction measures, but also as components of a broader energy-resilience strategy. WHO and IRENA identify solar photovoltaic and other clean-energy solutions as technically relevant options for improving the reliability and sustainability of healthcare electricity provision.

The potential value of a distributed PV system in a hospital therefore extends beyond the simple comparison between the cost of solar electricity and the cost of grid electricity. Its effects can be considered across several interconnected dimensions. From an economic perspective, locally generated electricity can reduce dependence on purchased grid energy and, where applicable, reduce fuel consumption associated with diesel backup generation. From an environmental perspective, replacing a portion of electricity generated through fossil-fuel-based sources can contribute to reducing greenhouse-gas emissions. From an operational perspective, appropriately designed generation and storage capacity can increase the ability of the facility to maintain selected essential loads during grid interruptions. Finally, from an institutional perspective, improving the resilience of the energy system can support the continuity of healthcare services and reduce exposure to fluctuations in electricity prices, fuel availability, and external supply conditions

However, the technical suitability of a PV system cannot be determined solely from the availability of solar resources or the nominal electricity demand of a facility. Healthcare facilities have heterogeneous loads with different operating schedules, power requirements, and levels of criticality. Some equipment may operate continuously, while other loads are concentrated during particular periods of the day. In addition, the electricity demand of a hospital can vary according to clinical activities, occupancy, equipment usage, water pumping requirements, refrigeration needs, and other operational factors. An effective energy assessment must therefore examine the actual consumption profile of the facility and distinguish between total energy demand and the loads that require priority during an interruption. This makes the availability of reliable consumption data, electricity bills, equipment inventories, and operational information particularly important when evaluating potential energy interventions.

The Kenyan context provides a relevant setting in which to examine these considerations. The hospitals assessed through SEVA 4 AFRICA are connected to the Kenyan electricity grid, meaning that the central issue is not simply the absence of an electrical connection.

Instead, the assessment concerns the interaction between grid electricity, electricity expenditure, local supply interruptions, backup generation, and the operational requirements of the hospitals. Electricity bills provide information on the historical financial burden of electricity consumption, while equipment inventory and operational information provide a basis for understanding the composition and timing of demand. Information concerning outages and the use of backup generators is also relevant because it helps distinguish ordinary electricity consumption from the additional requirements associated with maintaining services during periods of grid disruption.

For these hospitals, a distributed photovoltaic system can consequently be considered as part of an integrated energy strategy rather than as an isolated renewable-energy installation. During periods of adequate solar irradiation, PV generation can supply daytime loads directly and reduce the amount of electricity purchased from the grid. Where battery storage is incorporated, excess generation can be stored and subsequently used to support selected loads. During grid outages, the combination of PV generation, storage, and appropriate load prioritization can contribute to maintaining essential hospital functions and reducing dependence on diesel-based backup generation. The effectiveness of such a configuration, however, depends on the relationship between the hospital's load profile, PV generation potential, storage capacity, electricity tariffs, backup requirements, and investment and maintenance costs.

The assessment of energy solutions for these hospitals therefore requires an interdisciplinary perspective. The problem involves technical questions concerning electricity demand, PV generation, storage, and system configuration, but it also involves economic questions related to investment costs, energy savings, operating expenditure, and financial feasibility. At the same time, procurement and implementation considerations influence whether a technically appropriate solution can be acquired, installed, operated, and maintained effectively. Risk management is also relevant because the value of an energy system depends partly on its ability to reduce exposure to grid interruptions and other supply uncertainties. Finally, the social dimension cannot be separated from the technical analysis: improved energy reliability has significance because it supports the continuity and quality of healthcare services delivered to patients.

Against this background, the hospitals assessed by SEVA 4 AFRICA provide a practical case through which the potential role of distributed photovoltaic generation can be examined. The preliminary assessment developed in this thesis brings together operational information, electricity consumption and billing data, equipment inventories, and considerations relating to grid reliability and backup generation. The purpose is not merely to determine whether solar energy can technically generate electricity at the selected facilities, but to examine how a photovoltaic solution could interact with existing energy consumption, operational requirements, economic conditions, and resilience needs. In this sense, the energy assessment serves as a bridge between engineering analysis and strategic decision-making, providing a basis for considering whether and under what conditions a distributed PV system could contribute to more reliable, economically sustainable, and resilient hospital operations.

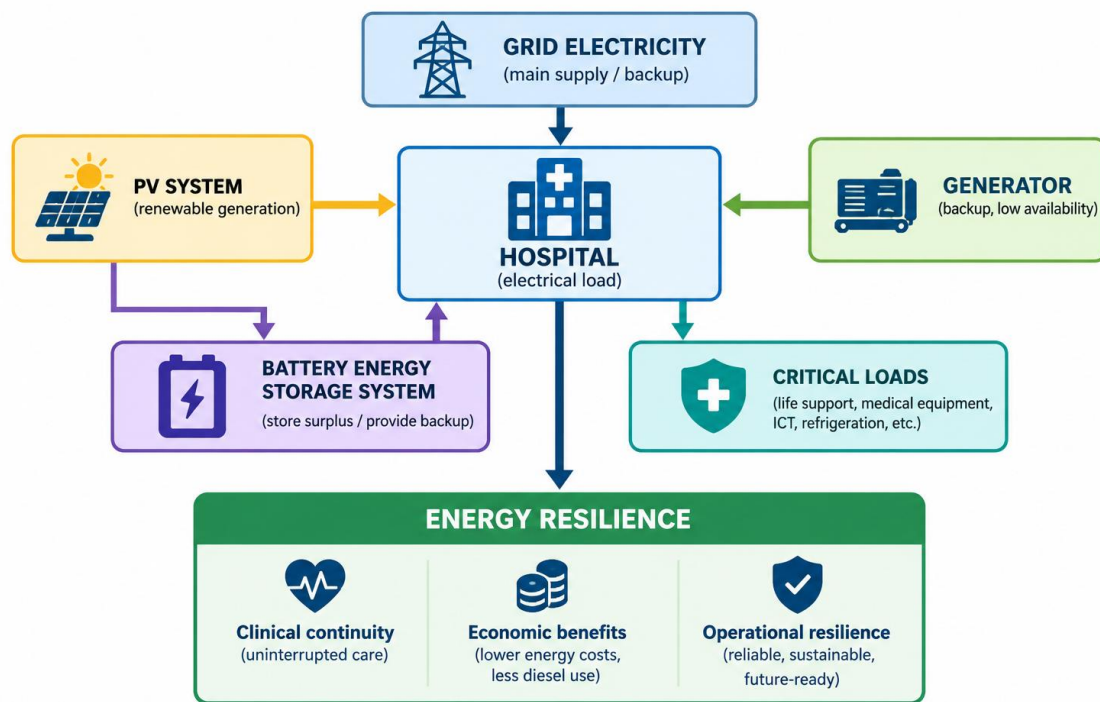


Figure 1.1 Energy-Healthcare-Resilience conceptual framework

Figure 1: Energy, health care , Resilience conceptual framework

1.2 Research problem

Although photovoltaic systems are increasingly considered as a means of reducing electricity costs and improving energy resilience in healthcare facilities, preliminary assessment is often constrained by incomplete, heterogeneous and inconsistent field information. This problem is particularly relevant in rural and resource-constrained healthcare facilities, where detailed interval-meter data, complete generator records, verified critical-load schedules,

structural information and final electrical drawings may not be available during the early stages of project development.

In the seven hospitals examined in this study, electricity consumption is documented through different evidence sources, including utility bills, equipment inventories, generator records, questionnaires, PV resource assessments, preliminary bills of quantities, requests for quotation and electrical design files. These sources do not always describe the same system configuration or provide information at the same level of accuracy. In addition, some project documents represent earlier design iterations and therefore contain alternative photovoltaic capacities, battery capacities and inverter configurations.

The resulting methodological problem is not simply the calculation of photovoltaic capacity. It is the determination of what can reasonably be concluded from incomplete evidence while maintaining traceability between the original data, assumptions, calculations and design recommendations. Treating missing information as zero, combining incompatible design iterations without reconciliation, or presenting preliminary estimates as final engineering decisions can create significant technical, financial and operational risks.

This study therefore addresses the problem of developing a transparent preliminary assessment methodology that distinguishes measured or documented information from assumptions, compares independent evidence streams, identifies uncertainty, and translates the resulting evidence into preliminary photovoltaic and battery-storage requirements. The approach is demonstrated through a portfolio of seven faith-based hospitals in western Kenya, with Our Lady of Lourdes Rangala Mission Hospital selected as the detailed case study because of the greater availability of project documentation.

1.3. Research Aim

The aim of this research is to develop and demonstrate a transparent and traceable methodology for the preliminary assessment of photovoltaic and battery-energy-storage systems in healthcare facilities using incomplete and heterogeneous field data, with application to seven faith-based hospitals in western Kenya and detailed validation through the Rangala Mission Hospital case study.

1.4. Research objectives

The study pursues the following objectives:

- To characterize and compare the electricity demand, energy expenditure, backup-generation dependence and preliminary photovoltaic potential of seven faith-based hospitals in western Kenya.
- To reconstruct the electricity-demand basis for Rangala Mission Hospital by triangulating utility-bill data, equipment inventories, generator information and project documentation.
- To develop a transparent preliminary photovoltaic-sizing approach that distinguishes observed evidence, calculated values and engineering assumptions.
- To reconcile alternative photovoltaic, battery-storage, inverter and system-architecture configurations contained in the project documentation and identify unresolved design inconsistencies.
- To evaluate the sensitivity of preliminary photovoltaic and battery requirements to key assumptions, including electricity demand, solar yield, critical-load demand, battery autonomy, self-consumption and load growth.
- To establish the technical information required to progress from preliminary assessment to detailed engineering, procurement and implementation.
- To develop a practical decision framework linking technical feasibility, energy resilience, economic considerations, risk management and maintainability in healthcare applications.

1.5 Research Questions

The research is guided by the following questions:

- What level and pattern of electricity demand for the seven hospitals can be supported by the available evidence, and how comparable are the resulting estimates?
- What preliminary photovoltaic capacity is indicated for the selected hospitals when electricity demand and site-specific photovoltaic productivity are considered?
- For Rangala Mission Hospital, how closely do bill-based and equipment-based demand estimates agree, and what assumptions explain any differences?

- Which assumptions and data uncertainties have the greatest influence on the preliminary photovoltaic and battery-storage requirements?
- What technical and operational conditions must be satisfied for a PV-BESS system to support defined critical hospital loads during grid interruptions?
- What information and decision gates are required before the preliminary concept can progress to detailed engineering, procurement and construction?

1.6 Research Gap

Previous studies of renewable-energy systems for healthcare facilities commonly address issues such as electricity access, photovoltaic generation, energy cost reduction, battery storage and system sizing. However, preliminary engineering decisions in real healthcare projects are frequently made before complete time-series load measurements, verified critical-load schedules, structural surveys and finalized electrical documentation are available.

A methodological gap therefore exists between conventional energy-system modelling, which can assume relatively complete and consistent datasets, and the practical conditions encountered during early-stage healthcare energy projects, where evidence may be distributed across utility bills, equipment inventories, generator records, questionnaires, preliminary quotations and evolving design documents.

The present study addresses this gap by treating data quality and traceability as explicit components of the preliminary engineering methodology. Rather than replacing missing information with unsupported assumptions, the approach classifies information according to its source and level of confidence, triangulates independent evidence streams, identifies contradictions between project documents, and separates preliminary screening results from requirements for detailed engineering.

The research contribution is therefore methodological rather than the development of a new photovoltaic technology or sizing equation. The study demonstrates how a transparent evidence-reconciliation process can be used to progress from incomplete field information to a defensible preliminary PV-BESS concept for healthcare facilities while explicitly identifying the uncertainty that must be resolved before implementation.

1.7. Scope, boundaries and contribution

The study covers seven faith-based healthcare facilities located in western Kenya: Tabaka, Asumbi, Lwak, Rangala, Nyabondo, Maseno and Awasi. Portfolio-level analysis is used for comparative screening, while Rangala Mission Hospital is examined in greater detail because it has the most complete combination of utility-bill information, equipment data, generator information, PV assessment, preliminary budget, request for quotation, string calculations and system-architecture documentation.

The study is intentionally limited to preliminary technical and strategic assessment. It does not constitute an issued-for-construction design and does not replace site surveying, structural engineering, protection coordination, detailed electrical design, regulatory approval, final procurement or commissioning.

The principal contribution is a traceable preliminary-assessment framework that:

- separates measured information from assumptions;
- triangulates electricity bills, equipment inventories and generator records;
- identifies data-quality limitations;
- reconciles alternative project-design iterations;
- links PV sizing with critical-load and battery considerations;
- identifies technical, economic and operational uncertainties; and
- defines the information and decision gates required before implementation.

This approach is intended to reduce false precision and provide a defensible transition between feasibility assessment and detailed engineering.

CHAPTER 2: KENYAN ENERGY CONTEXT AND HOSPITAL PROFILES

2.1 Electricity as critical healthcare infrastructure

Healthcare loads differ in criticality, operating schedule, starting current and tolerance to interruption. Vaccine refrigeration, selected laboratory devices, emergency lighting, communications and essential clinical equipment may require continuous supply. Pumps,

kitchens and administrative loads may tolerate scheduling. A resilient system should therefore distinguish essential and non-essential circuits, because powering every load during an outage can make storage uneconomic while failing to prioritize clinical services.

Energy reliability has four dimensions: adequacy, continuity, quality and recoverability. Adequacy means sufficient power and energy; continuity concerns outage frequency and duration; quality covers voltage, frequency, phase balance and transients; recoverability describes how quickly the hospital can restore service after failure. A PV-battery system contributes to all four only when correctly integrated with grid, generator, bypass and protection arrangements.

2.2 Kenyan electricity and renewable-energy setting

Kenya has expanded electricity access through grid extension and off-grid initiatives, while renewable energy forms an important part of the national supply mix. At facility level, however, tariff exposure, outages and weak local distribution may remain significant. Distributed solar can reduce demand at the point of use and complement national electrification. The project's western Kenyan sites are close to the equator and show relatively stable annual solar productivity, which supports year-round generation but does not eliminate seasonal cloud and rainfall effects.

Solar-PV design and installation in Kenya are regulated activities. The Energy (Solar Photovoltaic Systems) Regulations require appropriately licensed people for design and installation. A hospital project must also comply with applicable electrical codes, utility interconnection conditions, occupational safety requirements and equipment standards. The thesis therefore treats licensing, approvals and inspection as design inputs rather than administrative afterthoughts.

2.3 Western Kenya and the selected mission hospitals

The seven hospitals demonstrate substantial variation in electricity demand despite being located within the same broad western Kenyan geographical region. The screening estimates range from approximately 51 kWh/day at Rangala and Awasi to approximately 1,179 kWh/day at Tabaka. By comparison, the reported annual photovoltaic specific yields range from 1,460.43 to 1,594.31 kWh/kWp/year.

The relative variation in photovoltaic resource is therefore substantially smaller than the variation in electricity demand. This indicates that, at the portfolio screening stage, differences in hospital demand are more influential in determining preliminary photovoltaic capacity than differences in annual solar productivity.

This finding has an important programme-level implication. A standardized photovoltaic programme should not assume that hospitals within the same geographical region require identical system sizes. Instead, standardization should focus on the assessment methodology, documentation, equipment-quality requirements, monitoring, training, maintenance and procurement processes, while the generation and storage capacities remain site-specific.

The comparison also demonstrates that electricity demand alone is insufficient for determining project priority. Lwak, for example, records comparatively high diesel expenditure relative to its electricity expenditure, while Rangala and Awasi have similar rounded daily electricity demand but substantially different recorded diesel expenditure. These differences indicate that generator dependence, outage exposure and the operational importance of backup generation must be considered alongside total energy consumption.

The portfolio therefore supports a differentiated approach based on at least five dimensions: energy demand, energy expenditure, backup-generation dependence, clinical criticality and data readiness. A hospital with high electricity consumption may offer substantial potential for energy-cost reduction, while a smaller facility with frequent outages and highly critical loads may provide greater resilience value despite having a lower total energy demand.

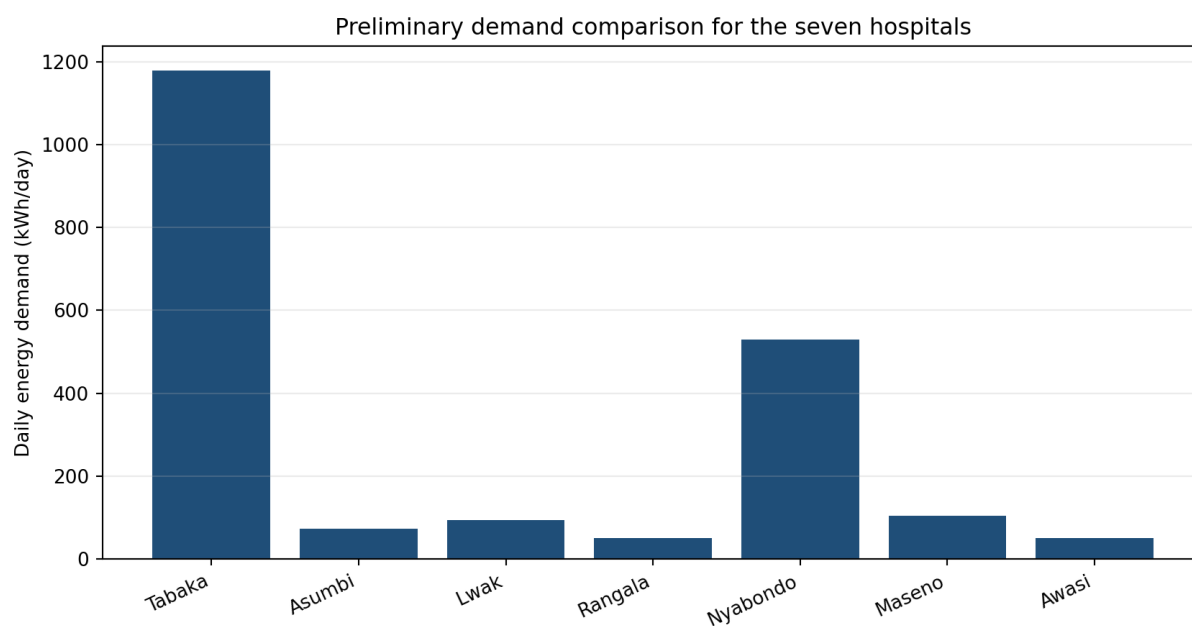


Figure 2. – Preliminary comparison of daily electricity demand across the seven hospitals. Source: MLT Project S4A workbook.

Hospital	County	Specific yield (kWh/kWp/y)	Demand (kWh/day)	Preliminary (kWp)
Tabaka	Kisii	1,460.43	1,179	295
Asumbi	Homa Bay	1,504.62	73	18
Lwak	Siaya	1,594.31	94	22
Rangala	Siaya	1,573.98	51	12
Nyabondo	Kisumu	1,497.51	530	129
Maseno	Kisumu	1,510.47	105	25
Awasi	Kisumu	1,550.14	51	12

Table 1: Preliminary comparison of daily electricity demand across the seven hospitals

Source: Data collected in Questionnaires

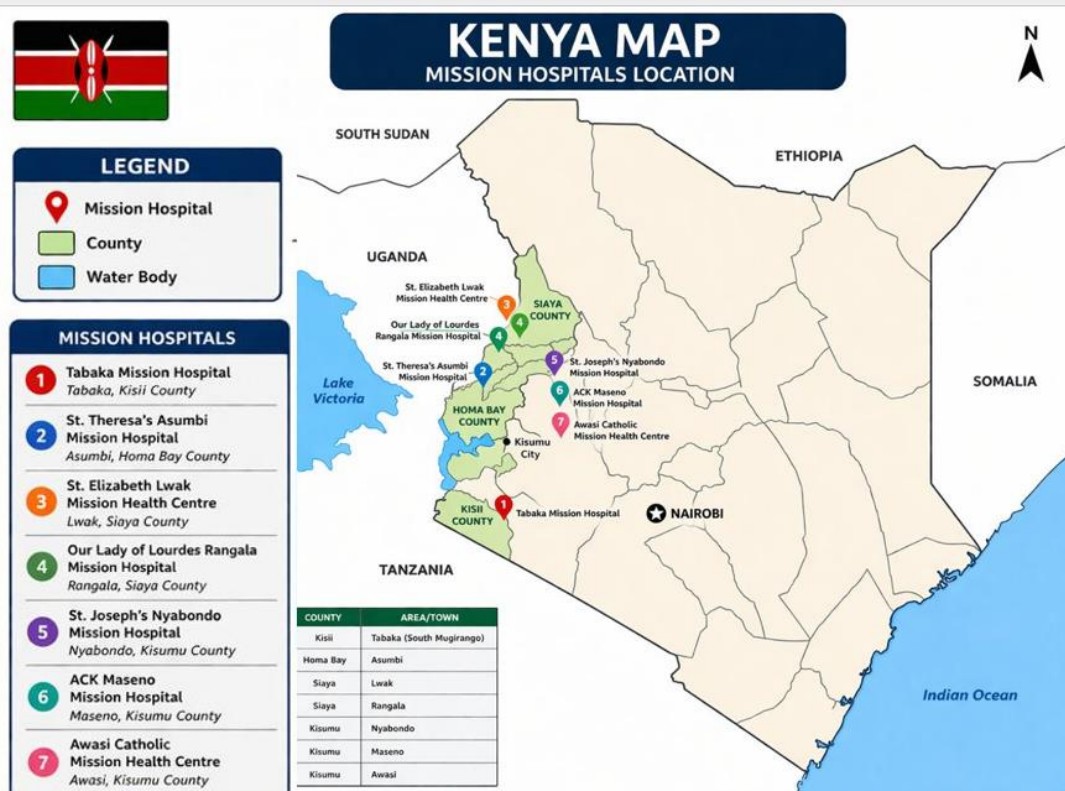


Figure 3: Geographic distribution of the seven healthcare facilities assessed in western Kenya, based on project coordinates.

2.4 Tabaka Mission Hospital – Kisii County

Tabaka Mission Hospital is the largest energy user in the seven-hospital portfolio. It is located in Kisii County in the Gusii Highlands at approximately latitude -0.746889 and longitude 34.667070 . The project information records about 250 beds, 45 buildings, a three-phase electrical system, two meters electricity and a 250 kVA standby generator. Its role includes maternal care, surgery, inpatient services and community healthcare. The size of the campus and the number of buildings make its electrical system more complex than the systems of the smaller hospitals.

The portfolio assessment estimates overall electricity demand at approximately 1,179 kWh/day. Annual electricity expenditure is reported as €53.991, while annual diesel expenditure is about €41.659. These figures indicate a strong dependence on both the utility grid and backup generation. The high diesel cost suggests that grid interruptions or operational constraints have a significant financial impact. For a hospital of this size, energy reliability affects many departments simultaneously, and a simple roof-mounted system serving one distribution board would not necessarily address the full resilience need.

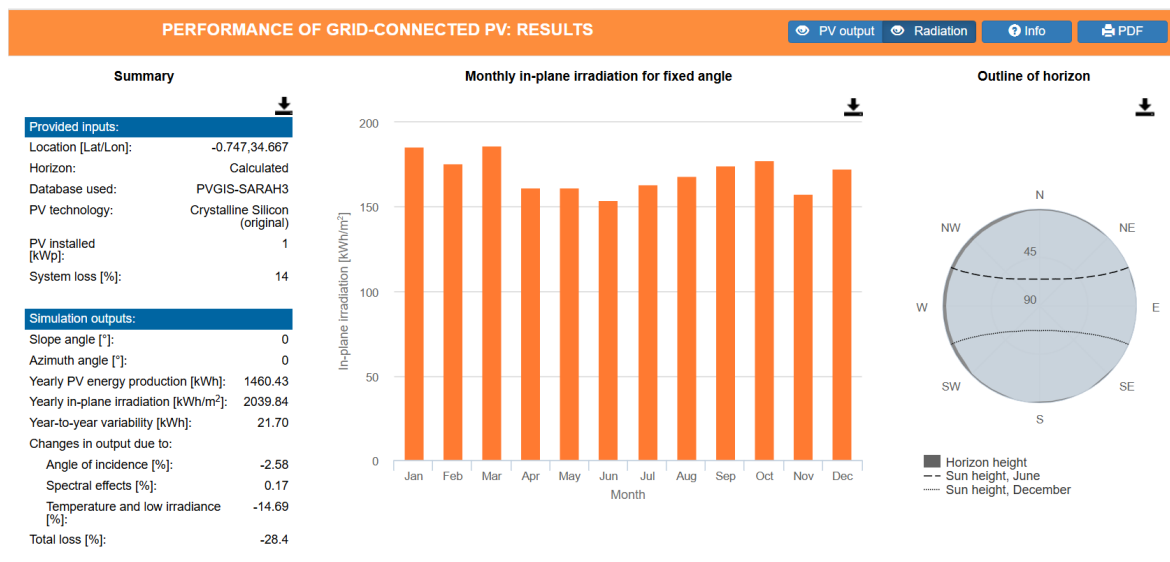


Figure 4: PVGIS results for Tabaka Hospital.

The recorded specific photovoltaic producibility is 1,460.43 kWh/kWp/year, equivalent to about 4.00 kWh/kWp/day. This is the lowest value among the seven sites, although it still represents a useful solar resource. Kisii's higher elevation, frequent rainfall and cloud cover can reduce production compared with warmer locations around Lake Victoria. Using the preliminary energy-balance method, the estimated PV capacity is approximately 295 kWp. This value should be treated as a program-level screening result because no complete hourly profile, roof survey, switchboard inventory or storage design was supplied.

Tabaka requires dedicated detailed study rather than direct scaling of Rangala's 12 kWp design. The next phase should map its 45 buildings, two meters, major clinical loads, generator-supported circuits and suitable roofs or ground areas. Rangala remains useful as a reference for the sequence of data collection, bill analysis, PVGIS assessment, protection review and commissioning, but Tabaka will require higher-voltage distribution considerations, multiple connection points and a formal phased implementation strategy.

2.5 FSJ St. Theresa's Asumbi Mission Hospital – Homa Bay County

FSJ St. Theresa's Asumbi Mission Hospital is located in Homa Bay County at approximately latitude -0.620410 and longitude 34.614650 . The project information identifies a 35-bed facility with a three-phase electrical system, one grid connection and a 66 kW backup generator. The hospital serves the Lake Victoria Basin and contributes to referral services, maternal and child healthcare and training of healthcare personnel. Reliable electricity is therefore necessary for clinical activities as well as teaching, administration and communication.

The screening workbook reports average energy consumption of about 73 kWh/day. Annual electricity expenditure is approximately €4.022 and diesel expenditure about €2.347. Compared with Rangala, Asumbi has higher recorded energy use and much greater generator expenditure. This suggests that backup generation is more operationally important, although the absence of generator run-hour and fuel-volume detail prevents a precise reliability assessment. The facility's energy strategy should seek both cost reduction and improved continuity during utility interruptions.

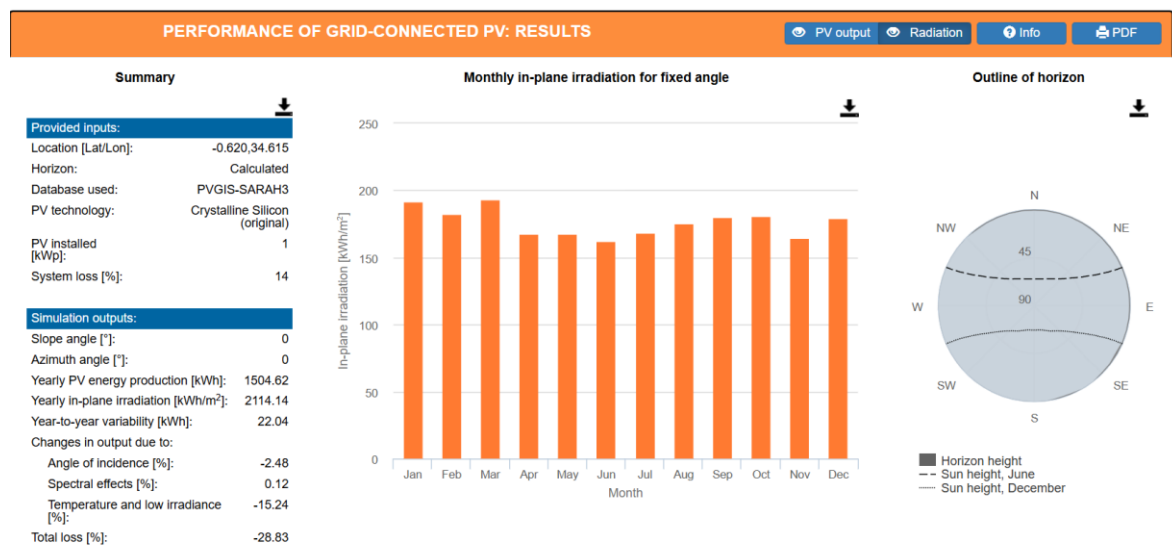


Figure 5: PVGIS results for Asumbi Hospital.

PVGIS-based specific producibility is reported as 1,504.62 kWh/kWp/year, or about 4.12 kWh/kWp/day. Dividing preliminary daily demand by this yield gives an estimated PV capacity of approximately 17.7 kWp, rounded to 18 kWp in the project presentation. Homa Bay generally has strong equatorial solar availability, but seasonal rainfall, humidity and cloud influenced by Lake Victoria will affect hourly and monthly generation. Battery

capacity should be determined from the essential night-time and outage load, rather than by applying Rangala's storage ratio automatically.

A detailed Asumbi assessment should collect twelve complete months of bills, generator fuel and run hours, an inventory of laboratory and maternal-care equipment, an essential-load schedule and three-phase interval measurements. Rangala's system can serve as a methodological reference for a hybrid architecture, but Asumbi's larger generator dependence may justify a different control strategy and autonomy target.

2.6 St. Elizabeth Lwak Mission Hospital – Siaya County

St. Elizabeth Lwak Mission Hospital is located in Siaya County at approximately latitude -0.140520 and longitude 34.356890 . It is recorded as a 45-bed hospital with a three-phase supply, one grid meter and a 44 kVA backup generator. The hospital provides primary and inpatient healthcare, immunization, safe-delivery support and preventive services to rural communities. In this context, electricity reliability is closely connected to maternal care, refrigeration, lighting, communications and basic diagnostic services.

The preliminary assessment reports daily energy consumption of approximately 94 kWh/day, annual grid-electricity expenditure of €4.437 and annual diesel expenditure of €4.651. Diesel expenditure slightly exceeds grid expenditure, making Lwak one of the clearest cases where generator dependence may create a strong economic and environmental incentive for solar hybridization. However, expenditure alone cannot reveal how often the generator operates, whether fuel purchases are complete, or which loads it supplies.

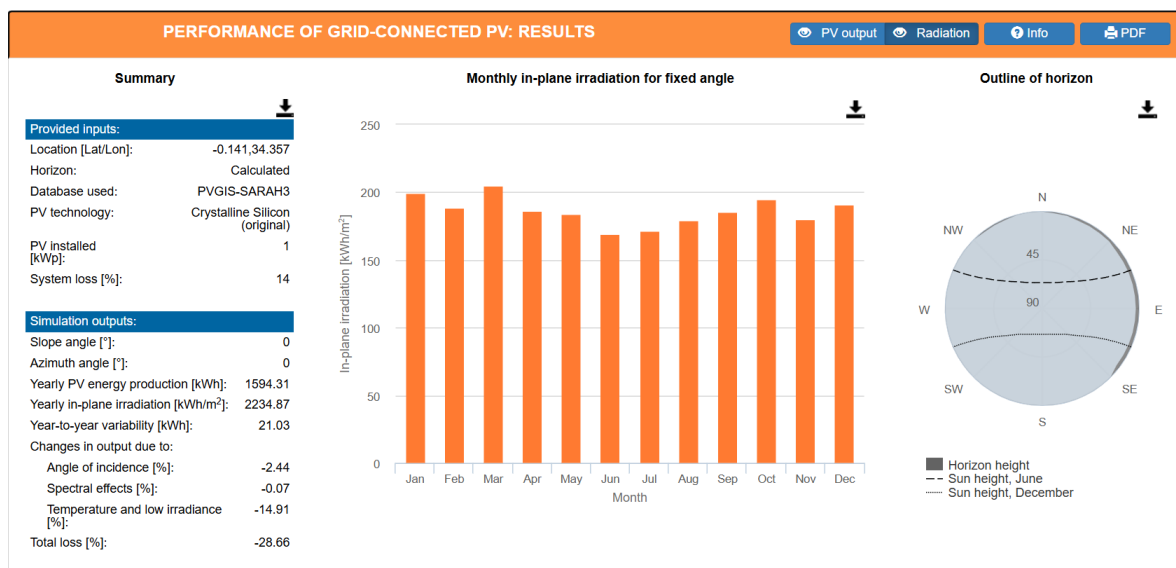


Figure 6: PVGIS results for Lwak Hospital.

Lwak has the highest recorded specific PV producibility in the portfolio: 1,594.31 kWh/kWp/year, equal to about 4.37 kWh/kWp/day. Its preliminary capacity is approximately 21.5 kWp, rounded to 22 kWp. The strong solar result reflects its geographic position in Siaya County, but actual performance will still depend on roof orientation, local shading, temperature, dust, rainfall and system availability. The high diesel share means an hourly analysis should examine whether solar and storage can displace generator operation during common outage periods.

The Rangala case is geographically relevant because both hospitals are in Siaya County. Rangala's PVGIS settings, local climate interpretation and equipment-survey method can therefore inform Lwak's next stage. Nevertheless, Lwak's demand, generator capacity and diesel dependence are higher. A separate load logger, essential-circuit definition, roof assessment and generator-integration study are required before selecting modules, inverters or batteries.

2.7 Our Lady of Lourdes Rangala Mission Hospital – Siaya County

Our Lady of Lourdes Rangala Mission Hospital is located at approximately latitude 0.153358 and longitude 34.332412 in Siaya County. The programme workbook records 60 beds, a three-phase supply, one grid meter and a 7 kVA generator. It provides healthcare services to a rural population and depends on electricity for refrigeration, water pumping, administrative equipment, clinical rooms, lighting and communications. Although Rangala is not the largest facility in the portfolio, it has the most complete set of project evidence.

The portfolio estimate is 51 kWh/day, while the detailed 2025 bill analysis gives 50.36 kWh/day from the grid and approximately 0.37 kWh/day from recorded generator fuel. Total average demand is therefore about 50.73 kWh/day. Annual electricity expenditure is reported as €3.492 and diesel expenditure as approximately €49. The low recorded diesel use may indicate relatively limited generator operation, but it may also reflect incomplete fuel records; an outage log and generator-hour meter should be checked.

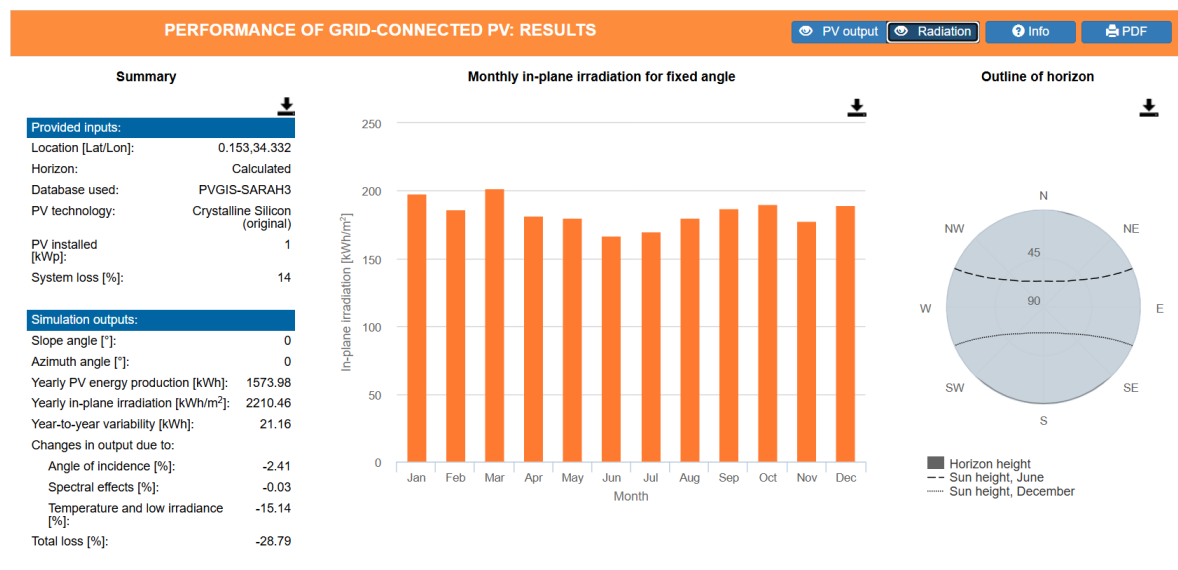


Figure 7: PVGIS results for Rangala Hospital.

Specific PV producibility is reported as 1,573.98 kWh/kWp/year, equivalent to 4.312 kWh/kWp/day. The first-order energy-balance calculation gives about 11.83 kWp, rounded to 12 kWp. The latest material concept uses twenty 620 W modules, equal to 12.4 kWp. Because Rangala also has a load assessment, bills, budget sheets, request for quotation,

Victron string checks and system architecture, it is used in Chapters 6–10 as the detailed reference case for the entire hospital program.

Using Rangala as the reference does not mean that its equipment is automatically suitable for the other hospitals. It provides a complete example of the analytical process: data collection, demand reconciliation, solar assessment, selection of a preliminary PV size, storage scenarios, architecture review, budgeting, risk management and implementation planning. The same process should be repeated using verified data for every site.

2.8 St. Joseph's Nyabondo Mission Hospital and Trauma Centre – Kisumu County

St. Joseph's Nyabondo Mission Hospital and Trauma Centre is located in Kisumu County at approximately latitude -0.381372 and longitude 34.978434 . The portfolio records around 150 beds and a three-phase electrical system with two meters. Its healthcare role includes emergency and trauma treatment, where electricity interruptions can directly affect time-sensitive services, diagnostics, sterilization, lighting and communications. The hospital is the second-largest energy user in the program after Tabaka.

Preliminary consumption is estimated at approximately 530 kWh/day. Annual electricity expenditure is reported as €25.489 and diesel expenditure as €16.737. These values show substantial dependence on purchased electricity and backup fuel. The generator rating is not recorded in the portfolio, which is an important data gap for a trauma facility. The detailed survey should identify which emergency loads are currently backed up, generator transfer time, fuel autonomy and whether any departmental UPS systems are in service.

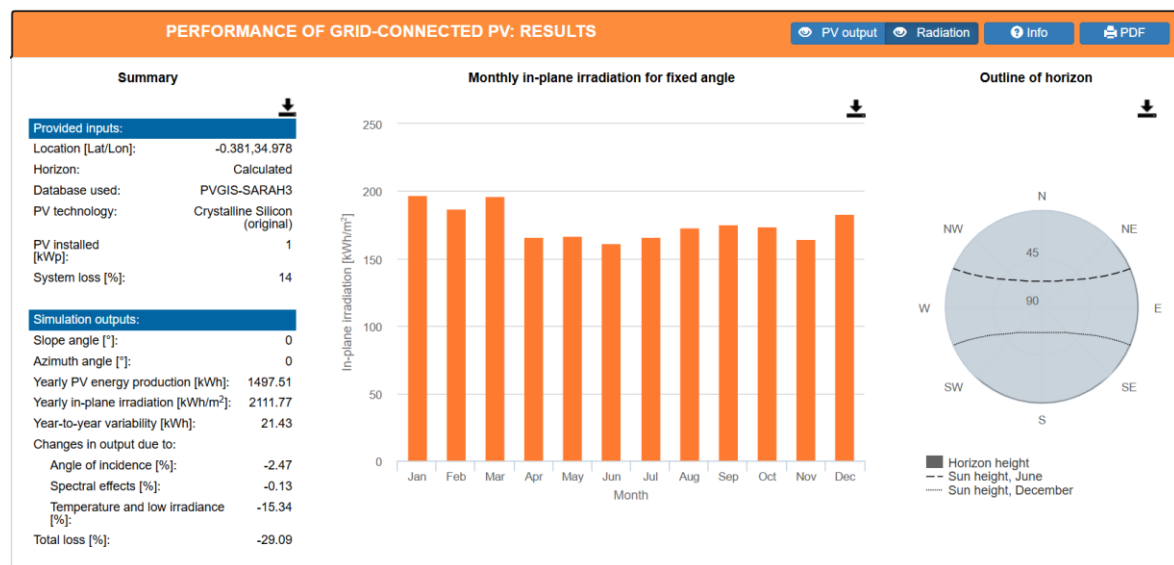


Figure 8: PVGIS results for Nyabondo Hospital.

Specific photovoltaic producibility is reported as 1,497.51 kWh/kWp/year, or about 4.10 kWh/kWp/day. The screening calculation gives approximately 129.2 kWp of PV. The system is therefore significantly larger than Rangala's and may need several roof zones, a ground-mounted area or a phased arrangement. Solar conditions in the Lake Victoria region are favourable, although cloud, rainfall, heat and humidity must be included in equipment selection, performance assumptions and maintenance planning.

Nyabondo should receive a full reliability-led design. In addition to energy savings, the study should model emergency and trauma loads during outages, evaluate redundancy and determine whether storage must support immediate continuity until the generator starts. Rangala's design process is a useful starting framework, but Nyabondo requires independent electrical coordination, structural design, protection studies and a much larger procurement package.

2.9 ACK Maseno Mission Hospital – Kisumu County

ACK Maseno Mission Hospital is located in Kisumu County at approximately latitude 0.000690 and longitude 34.611770, very close to the equator. The project records 80 beds, a three-phase electrical system and one grid meter. The facility supports comprehensive healthcare and health-worker training along an important transport corridor. Electricity is needed for clinical services, administration, learning activities, refrigeration, water and communication, making stable supply important to both patients and staff.

The preliminary workbook estimates demand at about 105 kWh/day. Annual electricity expenditure is approximately €6.934 and diesel expenditure about €756. The generator specification is not recorded. The lower diesel expenditure relative to grid cost may mean fewer outages, restricted generator use or incomplete records. Before system sizing, the hospital should provide generator information, outage history and a list of loads that must continue during grid failures.

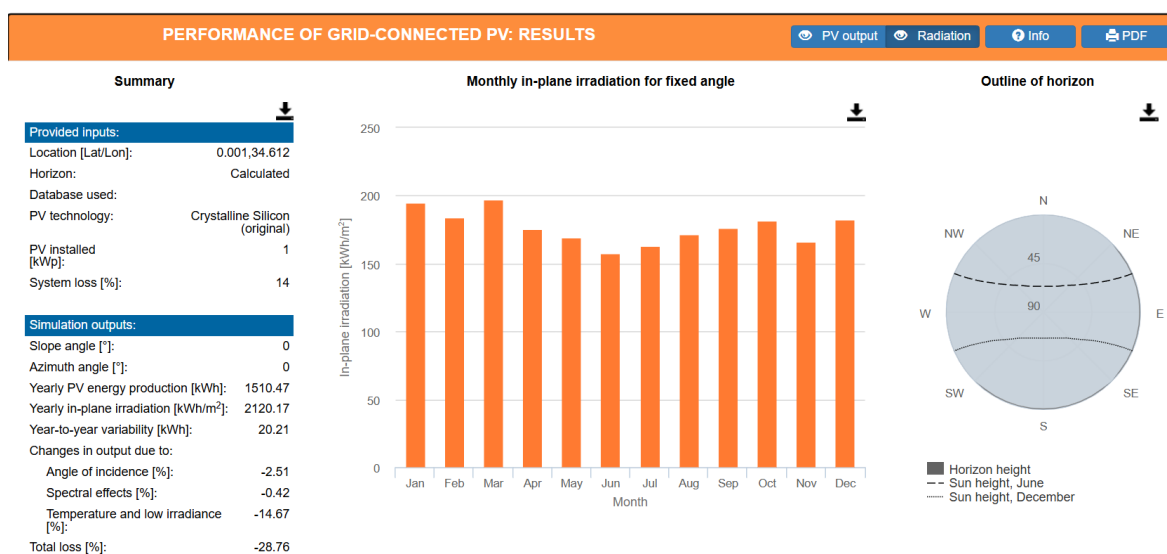


Figure 9: PVGIS results for Maseno Hospital.

The recorded specific producibility is 1,510.47 kWh/kWp/year, corresponding to about 4.14 kWh/kWp/day. The screening PV capacity is approximately 25.4 kWp, rounded to 25 kWp. Maseno's equatorial location provides broadly consistent daylight through the year, but energy production will still vary with rainfall, cloud cover, module temperature and site-specific shading. Monthly simulation is required to estimate grid savings and battery behaviour.

The future Maseno design should verify whether one centralized system or several building-level systems are preferable. Rangala's bill-analysis and design workflow can be reused, but the larger daily demand and unknown generator configuration require an independent architecture. The training role of the hospital also offers an opportunity to use monitoring data for staff awareness and education, provided cybersecurity and account ownership are properly managed.

2.10 Awasi Catholic Mission Health Centre – Kisumu County

Awasi Catholic Mission Health Centre is located in Kisumu County at approximately latitude -0.163588 and longitude 35.074213 . It provides outpatient, maternal, preventive and community health services to an underserved population. The project records a three-phase system, one grid connection and a 27 kVA generator, but the number of beds is not provided. Even as a smaller health centre, electricity is required for safe delivery, refrigeration, lighting, communications, water and basic diagnostic services.

Average consumption is estimated at about 51 kWh/day, the same rounded value as Rangala. Annual grid expenditure is reported as €3.287 and diesel expenditure as €1.011. Awasi therefore shows much higher diesel dependence than Rangala despite similar daily energy demand. This difference demonstrates why identical PV sizes do not necessarily justify identical battery and generator-control strategies. Outage timing and essential-load behavior must be measured.

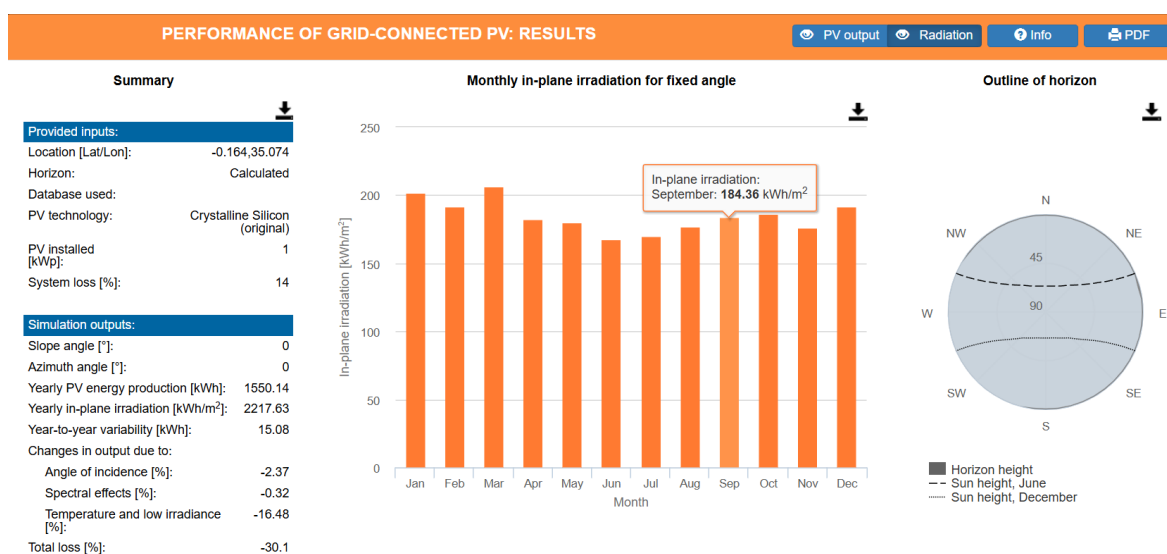


Figure 10: PVGIS results for Awasi Hospital.

Specific photovoltaic producibility is 1,550.14 kWh/kWp/year, or approximately 4.25 kWh/kWp/day. The preliminary PV capacity is about 12.0 kWp. This makes Rangala's 12–12.4 kWp concept a useful comparative reference. However, Awasi's 27 kVA generator, unknown bed count, different roof conditions and greater recorded diesel use require site-specific verification. A 12 kWp array could address annual energy, while storage capacity should be selected from maternity, refrigeration and night-time continuity requirements.

Awasi may be suitable for replication after the Rangala pilot because the preliminary PV capacities are similar. Replication should focus on standardizing the survey, quality requirements, monitoring, training and documentation—not copying every component without checking the facility. A controlled comparison between the two sites would help SEVA 4 AFRICA understand how different outage patterns influence storage value.

2.11. Comparative interpretation and program relevance

Hospital energy is a socio-technical system whose failure can propagate into patient safety, supply-chain disruption, reputational loss and reduced community trust. Distributed generation diversifies supply but also introduces cyber, fire, maintenance and spare-parts risks. Strategic design seeks balanced resilience: modular equipment, accessible bypass, trained staff, remote monitoring with secure credentials, clear escalation procedures and lifecycle funding.

CHAPTER 3: PHOTOVOLTAIC AND BATTERY ENERGY STORAGE SYSTEM FUNDAMENTALS

3.1 Solar resource and photovoltaic conversion

A photovoltaic cell converts incident solar radiation into direct current. Modules combine cells; strings connect modules in series to increase voltage; parallel strings increase current. Module nameplate power is stated at standard test conditions, which do not represent all field conditions. Actual output varies with irradiance, cell temperature, soiling, shading, mismatch, cable losses, conversion efficiency and availability. Preliminary energy estimation therefore combines installed peak power with site-specific yield or irradiation and a performance factor.

For energy-balance screening, annual PV energy can be written as $E_{PV} = P_{peak} \times Y_{spec}$, where P_{peak} is installed DC capacity and Y_{spec} is annual specific yield. The inverse sizing expression is $P_{peak} = E_{load} / Y_{spec}$. When daily values are used, units must remain consistent. This simple expression does not capture hourly mismatch, export constraints or battery losses, so time-series assessment is required for operational sizing.

3.2 Inverters, MPPT and hybrid operation

The inverter establishes the interface between DC generation, battery and AC loads. Grid-tied inverters synchronize with the utility and normally cease energizing the network when the grid fails. Hybrid or battery inverters can form a local AC bus for selected loads. MPPT controllers continuously adjust operating voltage so the array works near its maximum-power point. The selected architecture must define whether PV is DC-coupled, AC-coupled or mixed, how zero feed-in is enforced, how phases are served and which device controls the system during each operating state.

3.3. PV-BESS integrated system technology

A photovoltaic-battery energy storage system (PV-BESS) combines photovoltaic generation with an electrochemical energy storage system and power-conversion equipment to provide a coordinated electricity supply. While a conventional photovoltaic installation primarily produces electricity when solar radiation is available, the addition of battery storage allows part of the generated energy to be shifted in time. This makes the system capable of

responding not only to energy demand during daylight hours, but also to evening demand and, depending on the architecture, to selected loads during grid interruptions.

The basic functional elements of a PV-BESS installation are the photovoltaic array, maximum power point tracking (MPPT) equipment where applicable, battery energy storage, battery management system (BMS), power-conversion equipment, energy meter, protection devices and an energy management or control system. These elements operate together to determine how electricity is generated, stored, converted and supplied to the hospital loads. The exact configuration depends on whether the PV array is connected directly to a hybrid inverter, connected through separate grid-tied inverters, or connected to a DC bus shared with the battery.

Under normal grid-connected operation, photovoltaic generation is generally used first to supply local loads. If PV production is lower than the instantaneous hospital demand, the remaining demand can be supplied by the grid and, where configured, by the battery. When PV production exceeds the instantaneous load, the excess energy can be directed towards battery charging. Once the battery reaches its permitted state of charge, additional PV production may either be exported to the grid, if export is permitted, or curtailed when a zero-feed-in operating strategy is required. The operating sequence can therefore be represented conceptually as:

PV generation → local loads → battery charging → grid export or curtailment

while during periods of insufficient solar production:

PV generation + battery discharge + grid supply → hospital loads

The presence of a battery therefore changes the function of the PV system from a generation-only installation into a controllable energy system. The battery can absorb excess daytime generation and release energy when PV production is unavailable or insufficient. This temporal shift can increase photovoltaic self-consumption and reduce electricity purchased from the grid. In a hospital environment, the same storage capability can also be used to support selected essential loads during grid interruptions.

A particularly important distinction is between energy shifting and backup operation. Energy shifting refers to charging the battery when electricity is available or inexpensive and discharging it at another time to reduce grid consumption. Backup operation refers to maintaining electrical supply to defined loads when the normal grid source is unavailable. The same battery may perform both functions, but the control strategy must reserve

sufficient state of charge for the required backup service. Consequently, maximizing daily economic self-consumption should not compromise the minimum energy reserve required for hospital continuity.

3.3.1 PV-BESS operating modes

A hospital PV-BESS system can normally operate through several functional modes. In normal operation, the grid and PV system remain available, and the controller manages the interaction between PV generation, hospital loads and the battery. During periods of high solar production, PV energy can supply the hospital directly while surplus energy charges the battery. During periods of low solar production, the battery can be discharged according to the selected operating strategy.

During a grid outage, a battery inverter capable of forming a local electrical network can disconnect the protected loads from the utility supply and establish a stable AC supply for the designated backup circuits. PV generation can continue operating within this local network if the inverter architecture and control strategy allows it. This operating mode is commonly referred to as islanding or backup operation. It is fundamentally different from a conventional grid-following PV inverter, which normally shuts down when the external grid disappears because it cannot independently establish the required voltage and frequency reference.

For the Rangala hospital case, this distinction is particularly relevant. The proposed system is not intended simply to maximize annual photovoltaic energy production. It is also expected to interact with the existing grid and generator infrastructure and to support selected hospital loads during interruptions. The system should therefore be designed around a clearly defined backed-up distribution board containing essential loads. The battery capacity and inverter rating should subsequently be determined from the electrical demand and autonomy requirements of this protected circuit.

A conceptual sequence for the hospital application is therefore:

1. **Grid available, sufficient PV:** PV supplies local loads and surplus energy charges the battery.
2. **Grid available, insufficient PV:** PV supplies part of the load, with the grid supplying the remaining demand and the battery operating according to the energy-management strategy.

3. **High PV production and full battery:** Local loads are supplied first; excess production is curtailed or exported according to the configured operating mode.
4. **Grid failure:** The protected loads are isolated from the utility supply and supplied by the battery inverter, with PV contributing where operating conditions permit.
5. **Extended outage:** Battery discharge is managed according to the minimum state-of-charge limit and the defined critical-load priority. The existing diesel generator may provide an additional source where the system architecture permits coordinated operation.
6. **Grid restoration:** The system detects the return of the utility supply, performs the required synchronization and transfer sequence, and progressively returns to normal operating conditions.

The precise transition sequence must be verified during detailed engineering and commissioning because the interaction between the PV inverter, battery inverter, grid and standby generator depends on the selected equipment and control architecture.

3.3.2 AC-coupled and DC-coupled PV-BESS architectures

Two principal approaches can be used to integrate photovoltaic generation and battery storage: AC coupling and DC coupling.

In an AC-coupled system, the PV array is connected to a grid-tied PV inverter, while the battery is connected through a separate battery or hybrid inverter. Both systems exchange power through the AC distribution network. This architecture can be advantageous where an existing PV system must be retrofitted with storage because the battery can be added without replacing the existing PV inverter. It also provides flexibility in the selection and scaling of the PV and battery subsystems. However, energy transferred from PV to the battery and subsequently to the AC loads may pass through several conversion stages, resulting in additional conversion losses.

In a DC-coupled system, the PV array and battery are connected on the DC side through a common power-conversion system or compatible DC bus architecture. PV energy can therefore be directed to the battery without first being converted to AC and then back to DC. This can reduce conversion steps during battery charging and can provide efficient control of the interaction between PV generation and storage. However, DC-coupled systems require

careful compatibility checks between PV voltage, battery voltage, MPPT operating range, charge-controller ratings and inverter characteristics.

The choice between AC and DC coupling should therefore not be based only on nominal equipment ratings. It should consider the existing hospital electrical infrastructure, PV capacity, battery capacity, future expansion, conversion efficiency, control requirements, maintenance capability, redundancy and the intended operating modes.

For the Rangala project, the project files contain references to both Victron MultiPlus-II inverter/chargers and a Fronius grid-tied inverter. This suggests that an AC-coupled or mixed architecture may have been considered during the design process. However, the available documentation does not yet establish one final configuration. The detailed design should therefore issue one controlled single-line diagram showing the exact relationship between the PV array, MPPT controllers, battery, inverter/chargers, grid-tied inverter, grid connection, generator and protected hospital loads.

3.3.3 Battery management and energy management

The BMS and energy management system perform different but complementary functions. The battery management system supervises the battery itself and provides protection against operating conditions that could damage the cells. Depending on battery technology, the BMS can monitor cell voltage, temperature, current, state of charge and other battery operating parameters. It can also communicate permitted charging and discharging limits to the inverter or energy-management system.

The energy management system (EMS) operates at the system level. It determines how available PV generation, battery storage, grid electricity and, where applicable, generator supply should be coordinated. EMS can implement strategies such as maximizing PV self-consumption, maintaining a minimum state of charge, limiting grid import, preventing unwanted export, and reserving battery energy for backup operation.

For a hospital, the EMS should not be optimized exclusively for economic energy savings. The control strategy should include a minimum reserve for critical services where battery backup is part of the resilience objective. For example, if a battery is permitted to be discharged completely during normal evening operation, insufficient energy may remain when an unexpected grid interruption occurs. A minimum state-of-charge reserve therefore acts as an operational security margin.

The EMS should also define the interaction with the diesel generator. Where generator integration is permitted by the selected equipment, the battery can potentially reduce generator operating time by supplying short duration loads and absorbing excess generator capacity during charging. The generator may subsequently be started when the battery state of charge falls below a defined threshold or when the outage duration exceeds the planned battery autonomy. Such control must be engineered carefully because generator minimum loading, frequency stability, inverter compatibility and protection coordination can affect safe operation.

3.3.4 PV-BESS sizing parameters

PV and battery sizing should be considered as related but distinct design problems. The PV array is primarily determined by the available solar resource, energy demand, available installation area, electrical constraints and desired reduction in grid purchases. Battery sizing is instead strongly influenced by the critical-load profile, required autonomy, allowable depth of discharge, efficiency, degradation and operating strategy.

The nominal battery capacity can be expressed as:

$$C_{nom} = \frac{E_{critical} \times t_{autonomy}}{DoD \times \eta_{sys}}$$

where C_{nom} is the nominal battery capacity in kWh, $E_{critical}$ is the average critical-load power in kW, $t_{autonomy}$ is the required autonomy in hours, DoD is the allowable depth of discharge and η_{sys} represents the relevant conversion efficiency.

This expression provides only a first-order estimate. In an actual hospital application, the critical load is time-dependent and may contain equipment with high starting currents or short-duration peaks. Consequently, an hourly or sub-hourly simulation is preferable to a calculation based only on average daily consumption. The model should determine battery state of charge over time and verify that the battery remains within its minimum and maximum operating limits under representative solar, load and outage conditions.

Battery power rating is also distinct from battery energy capacity. A battery may have sufficient energy in kWh to support a load for several hours but still be unable to supply the instantaneous power required by the connected equipment. The inverter and battery therefore need to be checked against both continuous power and transient requirements. Motors,

pumps, refrigeration compressors and other inductive equipment may have starting currents substantially higher than their steady-state consumption.

For Rangala, the project documents contain several storage concepts, including approximately 20 kWh, 24 kWh and 50 kWh. These values should not be interpreted as three competing final designs without considering their operating objectives. They represent different stages or scenarios in the preliminary design process. The final storage capacity should be selected after the essential-load panel, measured load profile, outage characteristics and required autonomy have been established.

3.3.5 Role of PV-BESS in hospital energy resilience

The principal technological value of PV-BESS in a hospital is its ability to combine renewable generation with controllable stored energy. PV reduces dependence on external electricity during periods of solar production, while the battery can shift energy to periods of lower PV availability. When the system is designed with appropriate islanding capability, the battery inverter can also provide a stable source to select loads during grid interruptions.

This does not mean that a PV-BESS system automatically provides complete hospital backup. The level of resilience depends on inverter power, battery capacity, critical-load selection, protection architecture, generator integration, equipment redundancy and the duration of the outage. A system designed to supply only refrigeration, emergency lighting, communications and selected medical equipment has substantially different requirements from a system intended to supply the entire hospital.

For this reason, resilience should be expressed in measurable terms. Relevant parameters include the percentage of critical load protected, maximum supported power, expected autonomy, number and duration of outages served, minimum battery state of charge, generator start conditions and recovery time following grid restoration. These parameters provide a clearer basis for engineering and commissioning than simply stating that the PV-BESS system provides “backup power.”

In the Rangala case, the PV-BESS concept should therefore be considered as part of a broader energy architecture consisting of **PV generation, battery storage, grid supply, standby generation, protected hospital loads and monitoring/control systems**. The objective is not to eliminate the grid or generator completely, but to coordinate the available energy sources so that normal energy consumption can be supplied efficiently while essential services remain protected during interruptions.

Technology consequently supports two complementary objectives: energy management and energy resilience. Energy management concerns the efficient use of PV generation and storage under normal conditions, including reduction of grid purchases and prevention of unnecessary energy export. Energy resilience concerns the ability to maintain selected hospital services when the primary electricity supply is unavailable. The final design should explicitly identify the requirements associated with each objective and avoid assuming that a battery size suitable for economic energy shifting will automatically provide adequate emergency autonomy.

3.4. Battery energy storage

Battery energy storage systems store electrical energy in electrochemical form and return it to the electrical system when required. In a PV-BESS application, the battery provides temporal separation between PV generation and electricity consumption and can also provide backup energy during grid interruptions. The useful performance of a battery depends not only on its nominal capacity, but also on its allowable depth of discharge, round-trip efficiency, operating temperature, degradation, state-of-charge limits, charging and discharging power and control strategy.

Battery capacity is normally expressed in kWh, whereas battery and inverter power capability is expressed in kW or kVA. These parameters must be considered separately. The energy capacity determines how long a defined load can be supported, while the power rating determines the maximum instantaneous electrical demand that can be supplied. Hospital loads such as pumps, refrigeration compressors and other motor-driven equipment may also produce short-duration starting currents that must be considered during inverter and battery selection.

The depth of discharge (DoD) defines the proportion of nominal battery capacity that can be used during normal operation. If a battery has a nominal capacity of 50 kWh and a minimum state of charge of 15%, approximately 42.5 kWh is available before conversion losses and other operating constraints are considered. The usable energy is therefore lower than the nameplate capacity.

Battery sizing for the present study should be based on the critical-load profile rather than on total hospital consumption alone. The design process should identify the loads that must

remain operational during a grid interruption, determine their hourly energy demand, define the required autonomy and then evaluate the resulting state-of-charge trajectory. This approach avoids oversizing the battery to supply non-essential loads while ensuring that clinically important services receive adequate protection.

The battery also requires appropriate environmental, electrical and operational conditions. Temperature, ventilation, enclosure arrangement, accessibility, protection against short circuits, isolation, fire-safety provisions and manufacturer installation requirements must be considered during detailed engineering. Battery monitoring and the battery management system are required to maintain operation within the permitted voltage, current and temperature limits.

For Rangala, the available project documentation contains several storage alternatives, including approximately 20 kWh, 24 kWh and 50 kWh. These values should be regarded as preliminary design scenarios rather than a final selection. The final battery capacity should be established following verification of the essential-load panel, measured demand, outage characteristics, required autonomy, inverter power capability and generator interaction.

3.5 Electrical safety, protection and earthing

PV arrays remain energized whenever irradiance is present. DC arcs can persist and are more difficult to interrupt than AC faults. Design must include correctly rated DC isolators, fuses or string protection where required, surge protection, cable insulation and routing, labeling, equipment bonding and earthing. AC protection must coordinate with inverter fault contribution and the existing hospital distribution system. Protection devices must be selected for voltage, current, prospective fault level, breaking capacity, polarity and installation environment.

Hospitals require additional attention to continuity and discrimination. A downstream fault should not unnecessarily disconnect the entire facility. Essential circuits should be separated and documented. Manual bypass must permit maintenance without unsafe improvisation. Surge protection is particularly important for exposed PV cabling and sensitive medical equipment. The RFQ's grounding extension, switchboards, isolators and reorganization of the radiology panel therefore form core safety scope, not ancillary material.

3.6 Monitoring, maintainability and lifecycle performance

Monitoring should record PV production, grid import, battery state, alarms, inverter status and, where useful, load consumption. Remote access supports diagnosis, but ownership of accounts, passwords, SIM subscriptions and data retention must be defined. Preventive maintenance includes visual inspection, cleaning according to soiling, torque checks, thermography, vegetation control, battery health review, firmware governance and verification of alarms and protective devices. A maintainable system uses locally serviceable components, clear documentation and an agreed spare-parts strategy.

3.7 Engineering Basis for the Present Study

The technical concepts described in this chapter are applied in the present study through a distinction between three related but different design objectives: energy production, energy management and energy resilience.

The first objective is energy production. The photovoltaic array should generate sufficient annual energy to provide a meaningful contribution to the hospital's electricity demand. At preliminary level, this can be assessed through the relationship between annual demand and site-specific photovoltaic productivity.

The second objective is energy management. The temporal mismatch between photovoltaic production and hospital demand means that annual energy equivalence does not imply that all photovoltaic energy can be consumed directly. Battery storage, load scheduling, grid interaction and, where applicable, export limitation determines the proportion of PV generation that can be effectively utilized.

The third objective is energy resilience. Resilience cannot be established solely from PV capacity or battery nameplate capacity. It depends on the critical-load power requirement, critical-load energy consumption, battery usable capacity, inverter power, minimum state of charge, outage duration, generator interaction and the ability of the control system to establish and maintain an isolated supply.

Consequently, the present study treats PV sizing and battery sizing as related but distinct analytical problems. The PV system is initially assessed against the hospital's energy requirement, while the battery system is assessed against the defined critical-load profile and required autonomy.

This distinction is particularly important for Rangala. A PV array may produce approximately the same annual energy as the hospital's annual electricity consumption while still being unable to supply the hospital continuously during a grid interruption. Conversely, a battery sized for full-hospital backup may be considerably larger and more expensive than a battery intended only to support essential clinical services.

The preliminary design methodology therefore uses annual energy balance for portfolio screening and reference PV sizing, while recognizing that final system sizing requires time-series load data, critical-load identification and battery state-of-charge simulation.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 Research design

This study adopts an applied, mixed-evidence case-study design combining quantitative energy analysis, comparative portfolio screening and qualitative engineering-risk assessment.

The research is organized into two analytical levels. The first level is a seven-hospital portfolio assessment intended to establish comparative electricity demand, expenditure, photovoltaic resource and preliminary PV capacity. The second level is a detailed case study of Rangala Mission Hospital, selected through purposive case selection because it contains the most complete and diverse set of project evidence.

The methodological structure consists of six sequential stages.

Stage 1: Evidence collection and classification. Project information was collected from structured questionnaires, utility bills, generator records, equipment inventories, geographic information, PVGIS outputs, preliminary budgets, requests for quotation, string-design calculations and system-architecture documents.

Stage 2: Data-quality and consistency assessment. Each evidence source was examined for completeness, date, origin, internal consistency and suitability for the intended calculation. Missing information was retained as unknown rather than automatically converted to zero.

Stage 3: Portfolio screening. Daily electricity demand, annual energy expenditure, diesel expenditure and photovoltaic specific yield were compared across the seven hospitals. Preliminary PV capacity was calculated using a common energy-balance method.

Stage 4: Detailed Rangala demand reconstruction. Rangala's electricity demand was independently assessed using utility-bill information, generator fuel information and a bottom-up equipment inventory. The results were compared to identify agreement and uncertainty between the evidence streams.

Stage 5: Preliminary technical assessment. PV capacity, monthly solar production, battery-storage scenarios, inverter requirements, system architecture, protection considerations and critical-load requirements were assessed.

Stage 6: Decision and risk assessment. The resulting design was evaluated against technical, economic, environmental, operational and strategic criteria. Unresolved issues were converted into explicit requirements for site survey, detailed engineering, procurement and commissioning.

The methodology is therefore intended not to produce a construction-ready design, but to establish the highest level of engineering conclusion that can be justified by the available evidence.

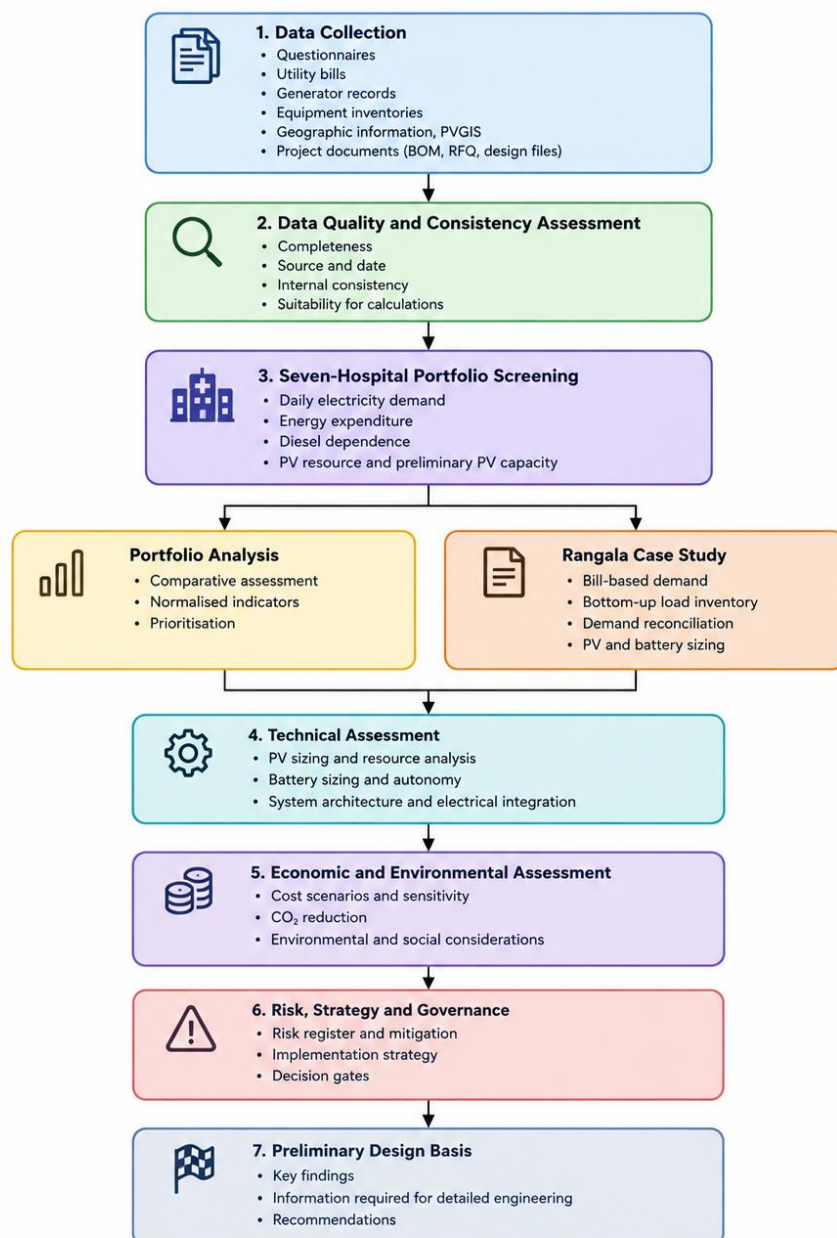


Figure 11: Summary of the methodology Used

4.2 Data sources and collection

Evidence stream	Purpose	Main limitation
Structured questionnaire	Facility characteristics, grid, generator, buildings and contacts	Self-reported; incomplete fields
Electricity bills	Purchased energy and cost profile	Billing period may not equal operating period
Diesel records	Backup generation estimate	Fuel may serve non-electric uses; efficiency uncertain
Load inventory	Bottom-up power and energy profile	Duty and coincidence factors assumed
PVGIS outputs	Specific yield and monthly resource	Does not capture nearby shading or roof constraints
RFQ and BOM	Implementation scope and component quantities	Contains copied wording and unresolved quantities
String tools	Voltage/current compatibility checks	Dependent on correct module/controller selection
System architecture	Functional integration concept	Requires final single-line verification

Table2 : Data sources and their purpose and limitations

Data completeness was checked through email, WhatsApp and online meetings. The project presentation records an iterative loop: questionnaire, completeness review, follow-up and preliminary assessment. This process is important because remote feasibility studies often fail when missing entries are treated as zeros. In this thesis, blank information is treated as unknown unless evidence supports another interpretation.

4.3 Energy-demand calculations

The bottom-up method calculates connected power for each appliance as quantity multiplied by rated power. Corrected demand applies utilization and coincidence coefficients. Daily energy is corrected power multiplied by operating hours. Day and night consumption are separated using a solar availability window from 07:00 to 17:00 in the project workbook. The method supports an hourly profile and allows direct PV, battery charge and battery discharge to be simulated.

The bill method converts purchased energy to daily consumption for each billing period. Rangala's workbook derives energy from monetary expenditure using an average unit energy cost of €0.19/kWh after currency conversion. This is acceptable for screening but introduces tariff and exchange rate uncertainty. The annual weighted means is more reliable than a simple means of monthly daily values because month lengths differ.

Generator electricity is estimated from purchased fuel and an assumed energy conversion. In the 2025 Rangala bill analysis, 45.48 litres are converted using 3 kWh/litre and divided by 365 days, producing 0.374 kWh/day. This small value should not be interpreted as generator capacity: the installed generator is reported as 7 kVA, while the annual energy record indicates infrequent use or incomplete fuel documentation.

4.3.1 Assumption and Uncertainty Management

Because several project inputs are incomplete or derived indirectly, assumptions are explicitly separated from observed data. Each assumption is assigned to a source, confidence level and expected influence on the resulting design.

Observed data includes values directly documented in electricity bills, project inventories, manufacturer documentation and recorded project files. Derived values are calculations based on observed data and stated mathematical relationships. Assumed values are introduced where direct evidence is unavailable, such as equipment utilization, coincidence factors, generator conversion efficiency or future load growth.

The study applies the following principle:

Missing information is treated as unknown rather than as zero unless an independent source provides evidence that the value is genuinely zero.

This distinction is particularly important for electricity consumption and generator operation. For example, the absence of a January electricity value in the Rangala bill dataset does not

demonstrate that the hospital consumed no electricity during that month. Similarly, recorded diesel purchases do not necessarily provide a complete measurement of generator electricity production because generator efficiency, operating hours and fuel usage conditions are not fully documented.

The principal assumptions used in the analysis are therefore recorded together with their expected influence on the results. Assumptions with potentially high influence, such as electricity demand, photovoltaic yield, critical-load demand, battery autonomy and self-consumption, should be tested through sensitivity analysis before final engineering decisions are made.

4.4 PV sizing and storage assessment

Portfolio PV power is calculated as daily energy divided by daily specific yield. For Rangala, 50.999 kWh/day divided by 4.312 kWh/kWp/day gives approximately 11.83 kWp. The latest component schedule uses $20 \times 620 \text{ W} = 12.4 \text{ kWp}$, providing a modest energy margin. Monthly yield values are then used to evaluate seasonal performance. Storage is evaluated with an hourly energy balance and state-of-charge constraints.

4.5 Quality control and limitations

Triangulation compares load inventory, bills, project summary and system-assessment outputs. Any unexplained divergence is recorded as an assumption or issue. The approach avoids false precision, but the analysis is limited by the absence of interval meter data, outage logs, a verified critical-load schedule, roof survey, confirmed tariffs, final quotations and structural calculations. Accordingly, results support a go-to-detailed-design decision rather than immediate construction.

CHAPTER 5: COMPARATIVE ASSESSMENT OF THE SEVEN KENYAN HOSPITALS

5.1 Site screening results

The portfolio workbook lists annual specific producibility between 1,460.43 and 1,594.31 kWh/kWp/year. This 9% spread is smaller than the variation in demand, which ranges from 51 to 1,179 kWh/day. Consequently, demand is the dominant driver of preliminary system size. Tabaka and Nyabondo together account for most of the identified portfolio capacity, while Rangala, Awasi and Asumbi are comparatively small projects that may be suitable for standardized modular approaches.

Site	Annual electricity expense (€)	Annual diesel expense (€)	Generator	Beds
Tabaka	53.991	41.659	250 kVA	250
Asumbi	4.022	2.347	66 kW	35
Lwak	4.437	4.651	44 kVA	45
Rangala	3.492	49	7 kVA	60
Nyabondo	25.489	16.737		150
Maseno	6.934	756		80
Awasi	3.287	1.011	27 kVA	

Table3: Site Screening results

5.2 Prioritization criteria

A portfolio program should not prioritize sites using energy demand alone. A multi-criteria decision should include clinical criticality, outage exposure, energy cost, data readiness, roof and electrical readiness, maintainability, implementation complexity and replicability. Rangala is attractive as a pilot because the nominal size is manageable and documentation is relatively advanced. A successful pilot can validate survey procedures, contracting, training, monitoring and handover before larger deployments.

5.3 Data maturity and comparability

The portfolio table creates comparability, but its apparent precision exceeds the underlying evidence in several cases. Some sites have missing generator information or incomplete facility metrics. Coordinating formats are inconsistent for Nyabondo. Expenditure does not necessarily indicate energy where tariffs, billing periods or unpaid balances differ. A formal data-quality score should accompany future screening, with categories for source, date, completeness, verification and confidence.

Recommended minimum data for every hospital includes twelve consecutive months of bills, interval or spot measurements on all phases, outage frequency and duration, generator run hours and fuel, critical-load schedule, roof drawings and photos, main-distribution-board details, earthing test, local shading, expansion plans and responsible staff. Standardizing these inputs reduces redesign and supports transparent prioritization.

5.4 Program-level procurement strategy

Portfolio procurement can aggregate compatible components while allowing site-specific engineering. Framework agreements may reduce unit cost and improve spare-parts commonality, but premature standardization can lock projects into inappropriate voltage, phase or storage architectures. A two-stage approach is preferable: first appoint qualified survey and detailed design support; then tender validated site packages with common performance, warranty, documentation and training requirements.

CHAPTER 6: RANGALA REFERENCE CASE: DETAILED ENERGY ASSESSMENT

6.1 Site description and available infrastructure

Our Lady of Lourdes Rangala Mission Hospital is located in Siaya County at approximately latitude 0.153358 and longitude 34.332412. The portfolio workbook records 60 beds, a three-phase electrical system, a single grid meter and a 7 kVA backup generator. Annual electricity expenditure is reported as €3,492 and diesel expenditure as approximately €49.31. These values indicate a grid-connected facility with limited recorded generator use.

6.2 Bill analysis

The 2025 bill worksheet reports grid-derived daily consumption ranging from approximately 23.23 to 129.27 kWh/day for months with recorded data. January has no separate entry, while February shows an unusually high value. This billing pattern suggests that January's consumption may have been included in the February bill. Consequently, the February value may reflect consumption accumulated over two months rather than an actual increase in daily demand. The total grid energy derived from the recorded bills is 18,380.58 kWh, equivalent to an average of 50.36 kWh/day when distributed over 365 days. Recorded generator fuel totals 45.48 litres, corresponding to an estimated 136.44 kWh/year using the assumed conversion factor of 3 kWh/litre, or 0.374 kWh/day. The combined annual-average demand is therefore approximately 50.73 kWh/day.

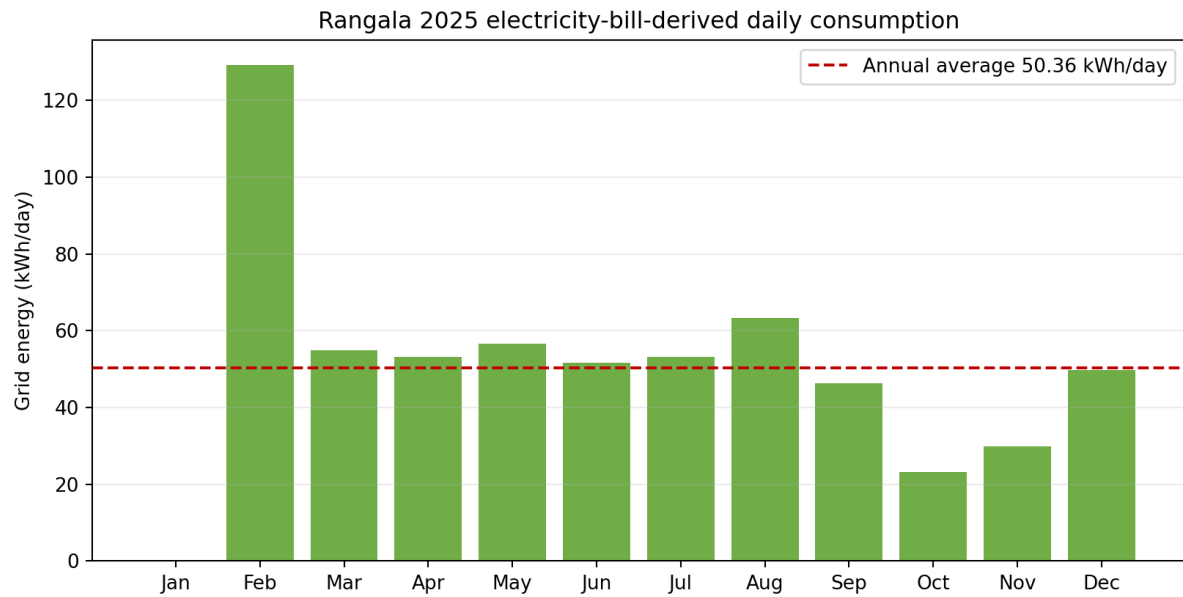


Figure 12 – Rangala Daily Electricity bills

Metric	Value	Interpretation
Grid energy	18,380.58 kWh/year	Derived from bills and assumed €0.19/kWh
Grid average	50.36 kWh/day	Annual energy divided by 365
Generator fuel	45.48 litres/year	Recorded purchases in Jan, May and Oct
Generator equivalent	0.37 kWh/day	Assumes 3 kWh electricity per litre
Combined average	50.73 kWh/day	Grid plus generator-equivalent energy

Table 4: Electricity-bill-derived Rangala daily consumption by month. January is missing rather than confirmed zero.

6.3 Bottom-up load profile

The consumption workbook lists water pumping, refrigeration, kitchen equipment, computers, printers, air conditioners and other hospital loads. Each row applies quantity, rated power, a combined utilization/coincidence coefficient and operating hours. For example, the 2.5 kW water pump is corrected to 1.5 kW and scheduled for three daytime hours, giving 4.5 kWh/day. Two 150 W refrigerators at a 0.5 factor contribute 3.6 kWh/day, while three 200 W freezers contribute 7.2 kWh/day.

Load	Quantity	Unit (kW)	power	Corrected power (kW)	Schedule	Energy (kWh/day)
Water pump	1	2.50		1.50	10:00–13:00	4.50
Refrigerators	2	0.15		0.15	24 h	3.60
Freezers	3	0.20		0.30	24 h	7.20
Kitchen load 1	1	0.46		0.414	11:00–13:00	0.83
Kitchen load 2	1	0.46		0.414	17:00–19:00	0.83
Computers	7	0.15		0.42	07:00–17:00	4.20
Printers	9	0.278		0.250	07:00–17:00	2.50
Air conditioners T1	3	2.40		0.72	08:00–17:00	6.48

Table5: Hospital load inventory and daily energy consumption.

The use of coefficients is reasonable for preliminary work but must be tested. A low coefficient may represent intermittent operation, diversity or uncertainty. For clinical refrigeration and critical loads, measured duty cycles and starting currents are preferable. Phase allocation is also absent; a 3.7 kW recorded peak in the portfolio sheet may be a measured snapshot rather than the maximum coincidence demand. Detailed design requires logging all three phases for at least one representative week, preferably spanning ordinary and high-demand conditions.

6.4 Reconciliation and design demand

The electricity demand estimate for Rangala is derived using two complementary approaches. The first is based on historical electricity-bill information and therefore represents observed purchased electricity, subject to the assumptions associated with tariff conversion and missing billing information. The second is a bottom-up estimate based on

identified equipment, rated power, operating schedules, utilization factors and coincidence assumptions.

The two methods serve different purposes. The bill-based method provides the strongest available evidence of historical electricity purchased by the facility, while the bottom-up method provides information about the composition, timing and operational characteristics of the demand.

A small difference between the two approaches would increase confidence in the preliminary demand estimate, while a substantial difference would indicate that one or more assumptions require further investigation. Possible causes include unrecorded equipment, incorrect operating hours, utilization factors, standby consumption, billing-period differences, equipment not included in the inventory or incomplete generator records.

The reconciliation should therefore not be interpreted simply as a test of whether one method is correct. Instead, it provides an indication of confidence that can reasonably be assigned to the preliminary design basis.

For the present study, the bill-derived estimate of approximately 50.36 kWh/day of grid consumption, together with the estimated 0.37 kWh/day generator-equivalent contribution, gives a combined screening value of approximately 50.73 kWh/day. The bottom-up estimate should be compared against this value before the preliminary design basis is finalized.

CHAPTER 7: RANGALA REFERENCE CASE: SOLAR RESOURCE AND PV SIZING

7.1 PVGIS resource results

The project uses the European Commission Joint Research Centre PVGIS tool. PVGIS provides solar radiation and photovoltaic-performance information using long-term meteorological datasets. For Rangala, the portfolio workbook records annual specific producibility of 1,573.98 kWh/kWp/year, equal to 4.312 kWh/kWp/day. The separate assessment provides monthly specific daily yield from 3.22 kWh/kWp/day in August to 4.96 in February, with a mean of 4.181.

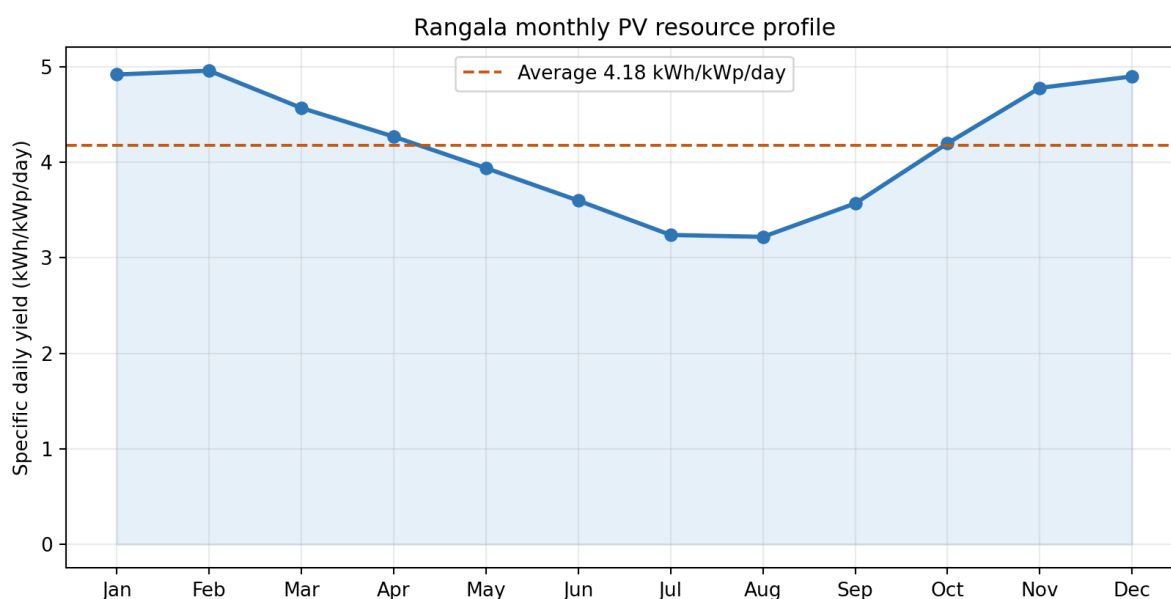


Figure 13 – Monthly Rangala specific PV yield used in the preliminary simulation. Source: PV System Assessment worksheet.

The difference between 4.312 and 4.181 kWh/kWp/day likely reflects different PVGIS runs, losses, orientation or data settings. Both values are plausible project inputs, but final design must retain the exact PVGIS report and parameters: database, technology, mounting, slope, azimuth, system losses and time period. Nearby shading and roof obstructions must be surveyed because PVGIS horizon data do not capture close buildings or trees.

7.2 Energy-balance sizing

Using the portfolio basis, $P_{\text{peak}} = 50.999 / 4.312 = 11.83$ kWp. Using the bill result of 50.73 kWh/day gives 11.76 kWp. A nominal 12 kWp array therefore corresponds closely to annual energy balance before considering curtailment, downtime, battery losses and load-growth margin. The latest component list uses twenty 620 W modules, producing 12.4 kWp DC. At 1,573.98 kWh/kWp/year, ideal model output is approximately 19.52 MWh/year, slightly above current grid-plus-generator demand of 18.52 MWh/year.

Design basis	Array definition	Capacity	Comment
Early worksheet	24 × 410 W	9.84 kWp	Older/undersized variant in PV System Assessment
Portfolio energy balance	Daily load ÷ daily yield	11.83 kWp	Rounded to 12 kWp
Latest BOM	20 × 620 W	12.40 kWp	Most recent material concept

Design basis	Array definition	Capacity	Comment
Assessment input	Direct entry	13.63 kWp	Alternative simulation requiring reconciliation

Table6: Comparison of preliminary PV sizing approaches for Rangala Hospital.

7.3 Monthly energy balance and performance losses

Annual equivalence does not guarantee monthly or hourly self-sufficiency. During lower-yield months, a 12.4 kWp array at 3.22 kWh/kWp/day produces about 39.9 kWh/day before any additional adjustment, below average demand. During February it produces about 61.5 kWh/day. Grid interaction and storage therefore remain important. If zero feed-in is imposed, surplus midday energy may be curtailed once loads and batteries are satisfied.

Losses arise from module temperature, soiling, mismatch, wiring, MPPT conversion, inverter conversion, battery charge and discharge, auxiliary consumption and availability. PVGIS specific yield usually incorporates a loss assumption, so losses must not be applied twice. Final energy modelling should use hourly PVGIS output and measured load, then simulate battery dispatch, grid import, curtailed energy, state of charge and generator start criteria.

7.4 Orientation and roof arrangement

The assessment sheet records a 14° slope and 0° azimuth, but the azimuth convention must be confirmed. Near the equator, shallow tilt can provide balanced annual production and facilitate cleaning, yet roof drainage, wind loading, access and shading determine the final arrangement. The RFQ refers to installation on OPD roofs and to a roof-parallel mounting system. A structural engineer must verify roof capacity, anchorage and waterproofing before installation.

7.5. Interpretation of Preliminary PV Capacity

The photovoltaic capacities calculated in this study represent preliminary energy-balance reference values rather than final engineering requirements.

The annual energy-balance method is useful for determining the approximate scale of photovoltaic generation required to offset a defined annual electricity demand. However, annual equality between PV production and electricity consumption does not imply hourly

energy independence. Electricity demand and photovoltaic generation occur at different times, and surplus photovoltaic production may be curtailed or exported when local demand and battery charging capacity are insufficient.

For Rangala, the calculated capacities of approximately 11.76–11.83 kWp therefore indicate the approximate scale of PV generation associated with the current annual energy demand. The 12.4 kWp configuration provides a modest increase relative to this calculated value and is consequently retained as a preliminary reference configuration.

This value should not be interpreted as an optimized or final PV capacity. Final capacity selection requires consideration of hourly demand, monthly production, self-consumption, battery operation, grid-import constraints, export limitations, future load growth, roof area, shading, electrical equipment ratings and system availability.

Accordingly, the principal output of this stage is not a final PV size but a defensible preliminary design range from which detailed engineering can proceed.

CHAPTER 8: REFERENCE ARCHITECTURE AND COMPONENT DESIGN

8.1 Functional architecture

The project files indicate a hybrid, three-phase concept integrating PV, grid, battery storage, monitoring and selected hospital distribution. The material alternatives refer to Victron MultiPlus-II inverter/chargers, SmartSolar MPPT RS 450/100 controllers, BYD low-voltage batteries, Cerbo GX monitoring and a Fronius grid-tied inverter in some variants. The RFQ, however, contains a different Fronius-based bill of materials copied from a larger installation, including two 20 kW inverters and a reference to 92 panels. This mismatch must be corrected before tendering.

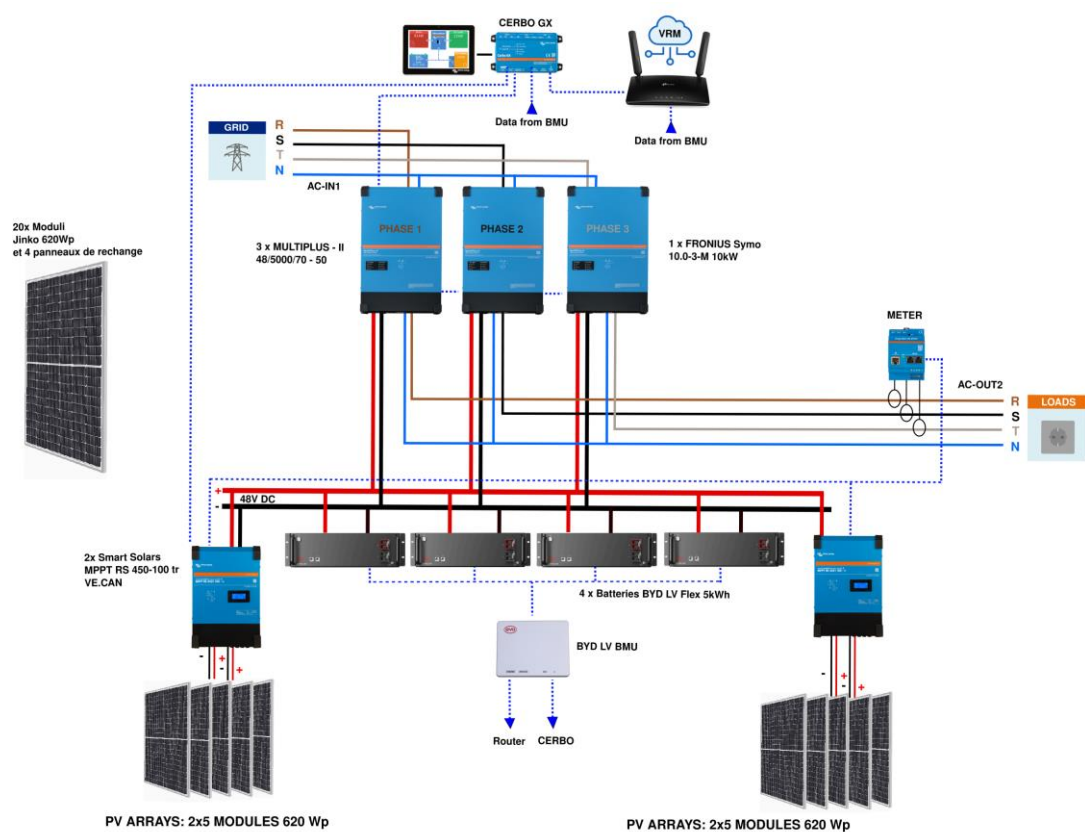


Figure 14 – Rangala 12 kWp system architecture supplied with the project files. The drawing must be validated against the final bill of materials and existing distribution system.

8.1.1 Reconciliation of Design Iterations

The project documentation contains several alternative photovoltaic and storage configurations. These differences are interpreted as design iterations rather than as simultaneous components of one final system. However, the existence of conflicting

configurations creates a procurement and engineering-control risk and therefore requires explicit reconciliation.

Design parameter	Earlier assessment	Portfolio basis	Latest component concept	Status
PV capacity	9.84 kWp	11.83 kWp	12.40 kWp	Preliminary reference: 12.4 kWp
Alternative PV input	—	—	13.63 kWp	Requires reconciliation
Battery	20 kWh	—	24 kWh	Requires autonomy study
Simulation battery	50 kWh	—	—	Scenario only
PV inverter	Alternative	—	Fronius 10 kW	Architecture to confirm
Hybrid inverters	—	—	3 × MultiPlus-II	Three-phase arrangement to confirm
MPPT controllers	Variant	—	2 × 450/100	Final string split required
Modules	24 × 410 W	—	20 × 620 W	Latest concept
RFQ module information	—	—	590–605 W	Must be reconciled
RFQ larger-system items	—	—	92 panels / 2 × 20 kW	Appears inconsistent with Rangala concept

Table7: Reconciliation of PV and battery design parameters.

The latest component schedule is therefore not automatically treated as the final engineering design. It represents the most recent identifiable project concept in the available documentation. Before procurement, all design iterations must be superseded by one

controlled equipment schedule, one single-line diagram, one string-design calculation and one approved bill of quantities.

8.2 PV modules and string configuration

The latest preliminary budget identifies Jinko 620 W bifacial N-type modules, twenty units, for 12.4 kWp. The RFQ instead states twenty modules in the 590–605 W range, five considered spares. If only fifteen modules are installed, operating capacity would be approximately 8.85–9.08 kWp, inconsistent with the 12 kWp objectives. Final procurement documents must distinguish installed quantity from spares and specify acceptable module electrical characteristics, dimensions, connector type, warranty and certification.

String design must verify open-circuit voltage at minimum temperature, maximum-power voltage at maximum cell temperature, short-circuit current, MPPT input current and controller power limits. The Victron tools show accepted configurations in the stored calculation variants, but the selected module index and controller values must be tied to an identifiable datasheet. A string check is valid only for the exact module and temperature assumptions used.

8.3 Inverters, charge controllers and phase arrangement

Three Victron MultiPlus-II 48/5000 units are listed in the preliminary component sheet, suggesting one unit per phase and approximately 15 kVA combined nominal inverter capacity. Two SmartSolar MPPT RS 450/100 units are listed for PV charging. A Fronius Symo 10 kW unit also appears, suggesting an AC-coupled contribution or an alternative design. The final architecture must clarify which elements are simultaneous and which belong to alternative concepts.

The MPPT RS workbook variant shows a 48 V system, 6.2 kWp total PV input in one calculation, module temperatures of 0–90°C and compatibility checks. The other string file shows 7.44 kWp for four modules in series and three parallel strings on a selected controller, with maximum PV voltage around 200.7 V against a 250 V limit and an accepted status. Because these figures do not directly equal the latest 12.4 kWp array, the final designer should rerun the manufacturer tool for each MPPT using the final split.

8.4 Battery system and autonomy

The project contains two storage concepts. The portfolio workbook records 20 kWh, while the PV System Assessment simulates 50 kWh with a 15% minimum and 50% initial state of charge. The preliminary material sheet lists four BYD Battery-Box LV Flex 6 kWh modules, equivalent to 24 kWh nominal. These variants should be understood as iterations. The final capacity should follow essential-load energy and target autonomy, not the PV size alone.

Storage variant	Nominal capacity	Evidence	Design implication
Portfolio screening	20 kWh	MLT Project S4A	Early site-level estimate
Component concept	24 kWh	4 × 6 kWh BYD modules	Procurement-oriented option
Simulation	50 kWh	PV System Assessment	Higher-autonomy scenario

Table8: Comparison of battery storage variants for Rangala Hospital.

8.5 Monitoring and zero feed-in

The RFQ requires configuration with zero feed-in, monitoring through a data-management interface and two days of testing, training and follow-up. Zero export must be implemented using a compatible meter, control logic and tested fail-safe behavior. Remote monitoring should be handed over to named hospital and SEVA administrators with documented access, alarm thresholds, data ownership and cybersecurity practices.

CHAPTER 9: ELECTRICAL INTEGRATION, SAFETY AND IMPLEMENTATION DESIGN

9.1 Existing-system interface

The existing three-phase supply, main distribution board, generator connection and radiology board must be surveyed before finalization. Required data include incoming protective device rating, earthing arrangement, neutral configuration, phase sequence, conductor sizes, prospective short-circuit current, generator changeover arrangement and phase loads. Any design based solely on remote documents risks incompatible ratings or unsafe neutral and earthing behavior.

9.2 Switchboards, cabling and protection

The RFQ includes PV DC, PV AC and radiology switchboards, 300 m each of positive and negative 6 mm² solar cable, 75 m of 5G25 mm² AC cable, 30 m of 5G16 mm² AC cable, 100 m of shielded CAT6, 100 m of 60 mm corrugated conduit, 15 m of trunking, service sockets and grounding material. Cable sizes must be recalculated for actual route, installation method, ambient temperature, grouping, voltage drop and fault protection. Quantities should be confirmed by site measurement.

Design check	Acceptance question
DC voltage	Does maximum cold-condition string Voc remain below every device and cable rating with required margin?
DC current	Are string, combiner, isolator and controller currents rated for design Isc and parallel strings?
AC ampacity	Do cables carry continuous current after derating for temperature, grouping and installation method?
Voltage drop	Are DC and AC voltage drops within the project criterion?
Fault protection	Are breaking capacity, discrimination and earth-fault protection adequate?
Surge protection	Are AC/DC SPD types, locations and earthing paths coordinated?
Isolation	Can PV, battery, inverter, grid and generator be safely isolated and locked out?
Labels	Are hazards, sources, shutdown procedure and circuits clearly identified?

Table 9: Electrical design verification and acceptance checks.

9.3 Construction and commissioning sequence

Implementation should follow controlled stages: verified survey; detailed design; approvals; procurement and factory document review; enabling civil and roof work; mounting; DC installation; equipment-room installation; AC integration; configuration; cold checks; staged energization; functional testing; outage simulation; monitoring validation; training; and handover. Work in live hospital areas requires permits, infection-control coordination, noise and dust controls, safe temporary supply and communication with clinical staff.

Commissioning should verify polarity, insulation resistance, continuity, earthing, protective-device settings, phase rotation, meter direction, communications, zero-export response, battery limits, generator and grid transitions, emergency shutdown and alarm reporting. A two-day operational follow-up is valuable, but the acceptance plan should define pass/fail criteria and require correction of defects before final payment.

9.4 Operation and maintenance

The handover package should include as-built single-line diagrams, equipment datasheets, settings backup, warranties, licenses, test results, asset register, spare-parts list, cleaning guidance, preventive-maintenance schedule, alarm matrix and escalation contacts. Hospital staff should be trained at user and technical levels. Training effectiveness should be demonstrated through practical tasks, not attendance alone.

CHAPTER 10: ECONOMIC AND ENVIRONMENTAL ASSESSMENT

10.1 Preliminary budget evidence

The preliminary budget workbook is incomplete and contains broken #REF! formulae in its summary sheet. A reference-price sheet lists panels, batteries, inverter/chargers, MPPT controllers, a Fronius inverter and communications equipment, while another sheet provides a 20-module component concept. Several unit prices appear to mix full currency amounts with abbreviated thousands, making the totals unsuitable for an investment decision without normalization. The thesis therefore presents cost structure and evaluation method rather than asserting an unsupported final CAPEX.

Cost category	Included items	Current evidence quality
PV generation	Modules, connectors, mounting structure	Module quantity and example price available
Power electronics	MPPT, hybrid inverter, grid-tied inverter, meters	Alternative architectures not reconciled
Storage	Battery modules, BMU, rack/cabinet	20/24/50 kWh variants
Electrical balance	Switchboards, isolators, SPD, cables, earthing	Quantities partly defined in RFQ
Services	Transport, installation, configuration, testing, training	Scope defined; final quotation absent
Contingency	Design development and unforeseen works	Early workbook applies 5% to subtotal

Table 10: Preliminary cost categories and evidence quality for the Rangala PV-BESS system.

10.2 Evaluation method

A bankable assessment should calculate baseline annual energy cost, expected self-consumption, avoided grid purchases, avoided diesel, operation and maintenance, battery replacement, inverter replacement, degradation, residual value and financing. Simple payback equals initial investment divided by annual net savings, but it ignores timing and replacements. Net present value discounts all lifecycle cash flows. LCOE divides discounted lifecycle cost by discounted useful energy supplied.

For Rangala, the project workbook reports annual electricity expenditure of €3,492 and diesel expenditure of approximately €49. These values set an upper bound on direct annual energy-cost savings unless tariffs rise or additional resilience value is monetized. With zero export, savings depend on self-consumption and battery dispatch. The system should not be

justified by annual energy balance alone; avoided outage cost, protected clinical services and reduced generator dependence are strategically important but must be transparently valued.

10.3 Sensitivity and uncertainty

Key sensitivities are installed cost, usable battery life, grid tariff escalation, self-consumption ratio, PV degradation, downtime and load growth. A lower-cost PV-only or small-storage system may deliver faster financial payback, while larger storage may deliver more resilience. Decisionmakers should evaluate at least three scenarios: energy-cost reduction, balanced hybrid, and resilience-priority. Each should state protected loads and expected outage service.

Variable		Low case	Base case	High case	Effect
Annual degradation	PV	0.3%	0.5%	0.8%	Higher degradation reduces lifetime yield
O&M as % CAPEX		1.0%	1.5%	2.0%	Higher O&M reduces net savings
Battery replacement		Year 15	Year 12	Year 8	Earlier replacement strongly affects NPV
Load growth		0%	2%/year	5%/year	Can improve self-use but exceed capacity
PV self-consumption		60%	80%	95%	Higher self-use increases avoided purchases

Table 11: Sensitivity analysis assumptions for the Rangala PV-BESS system.

10.4 Environmental and social benefits

PV generation reduces marginal grid purchases and diesel use. Emissions savings should use documented Kenyan grid and fuel emission factors applicable to the study year. Broader benefits include quieter operation, reduced local exhaust, improved service continuity and greater confidence in cold-chain and diagnostic services. Potential negative impacts include battery and electronic waste, roof penetrations, glare, fire risk and end-of-life management. Supplier take-back, recycling and safe battery handling should be included contractually.

CHAPTER 11: RISK, STRATEGY AND PROJECT GOVERNANCE

11.1 Risk management approach

A hospital PV project should maintain a live risk register from feasibility through operation. Risk is evaluated through likelihood and consequence, but clinical consequences must be considered separately from financial value. A low-cost fault can have high patient-safety impact. Owners should be assigned to risks, and mitigations must be verifiable actions with deadlines.

Risk	Likelihood	Impact	Mitigation
Incorrect load basis	Medium	High	Install three-phase logger; verify critical loads and future expansion
Roof structural weakness	Medium	High	Structural survey, anchorage design and waterproofing method
RFQ/BOM inconsistency	High	High	Issue one controlled equipment schedule and single-line diagram
Battery undersizing	Medium	High	Define autonomy and simulate measured essential-load profile
Protection incompatibility	Medium	High	Detailed fault/protection coordination and licensed review
Supplier dependence	Medium	Medium	Warranty, local service, spares and training requirements
Cyber/monitoring access loss	Medium	Medium	Account ownership, credential policy, local fallback and backups
Construction disrupts care	Medium	High	Phased works, temporary supply and clinical coordination
Weak maintenance funding	Medium	High	Lifecycle budget and service agreement
Extreme weather/lightning	Medium	High	Structural design, SPD, earthing and inspection

Table 12: Risk assessment and mitigation measures for the Rangala PV-BESS project.

11.2 Governance and decision gates

The project should use formal gates. Gate 1 confirms data completeness and pilot priority. Gate 2 accepts survey and design basis. Gate 3 approves detailed engineering and cost. Gate 4 authorizes procurement after technical-commercial evaluation. Gate 5 accepts installation readiness. Gate 6 authorizes energization after safety checks. Gate 7 completes handover after performance demonstration and documentation. A gate may return the project for correction; schedule pressure should not override clinical safety.

Gate	Required evidence	Decision
Gate 1	Complete data inventory	Proceed / collect data
Gate 2	Site survey	Approve preliminary design
Gate 3	Detailed engineering	Approve CAPEX
Gate 4	Tender evaluation	Approve supplier
Gate 5	Installation readiness	Start construction
Gate 6	Commissioning	Energize
Gate 7	Performance test	Handover

Table 13: Project decision gates and required evidence for implementation.

11.3 Stakeholders and responsibilities

SEVA 4 AFRICA acts as program sponsor and technical coordinator; hospital management defines clinical priorities, site access and operational acceptance; licensed Kenyan designers and installers hold regulated technical responsibilities; suppliers provide compliant equipment, warranties and documentation; the utility or competent authority addresses interconnection where applicable; and the academic study supports analysis but does not replace statutory design approval.

11.4 Resilience and security design principles

- Prioritize essential clinical services through a clearly labeled backed-up distribution board.
- Retain safe manual bypass and recovery procedures for failure of the automation layer.

- Avoid single points of failure where affordable; hold critical spares and configuration backups.
- Use modular expansion paths for load growth and future clinical equipment.
- Secure remote monitoring accounts and preserve local visibility when communications fail.
- Measure performance after handover and use evidence to refine later hospitals in the program.

CHAPTER 12: CONCLUSIONS AND RECOMMENDATIONS

12.1 Main findings

This study developed and demonstrated a transparent preliminary methodology for assessing photovoltaic and battery-energy-storage opportunities in healthcare facilities using heterogeneous and partially incomplete project information. The methodology was applied to seven faith-based hospitals in western Kenya, with Our Lady of Lourdes Rangala Mission Hospital examined as the detailed reference case.

The portfolio analysis demonstrates substantial variation in electricity demand between the seven hospitals. The preliminary daily demand estimates range from approximately 51 kWh/day to 1,179 kWh/day, while annual photovoltaic specific productivity varies over a substantially narrower range. This indicates that hospital electricity demand, rather than differences in annual solar resource alone, is the principal determinant of preliminary PV system scale at the portfolio screening stage.

The comparison also demonstrates that hospital energy requirements cannot be evaluated using electricity consumption alone. Diesel expenditure, generator availability, clinical criticality, facility size, electrical infrastructure and data completeness affect the appropriate energy strategy. Consequently, a common assessment methodology is more appropriate for the programme than a common system size.

For Rangala Mission Hospital, the best-supported grid-energy estimate from the available 2025 billing information is approximately 50.36 kWh/day. The recorded generator fuel corresponds to approximately 0.37 kWh/day when converted using the project's assumed 3 kWh/litre factor. The resulting combined screening value is approximately 50.73 kWh/day. The generator-derived component should be treated as an estimate rather than a direct measurement because generator efficiency and operating records have not been independently verified.

Using the reported specific PV productivity of 1,573.98 kWh/kWp/year, the preliminary energy-balance calculation gives approximately 11.76–11.83 kWp depending on the demand basis used. The latest project concept of 20×620 W modules corresponds to 12.4 kWp and can therefore be retained as a preliminary reference configuration. It should not, however, be interpreted as a final or optimized system size.

The project documentation also demonstrates the importance of design-document reconciliation. Alternative PV capacities of approximately 9.84, 11.83/12, 12.4 and 13.63 kWp are present, together with battery concepts of approximately 20, 24 and 50 kWh and alternative inverter configurations. These differences appear to represent successive design iterations, but they create a significant engineering and procurement risk unless superseded by one controlled equipment schedule and one verified single-line diagram.

The study therefore concludes that the available evidence is sufficient to establish a defensible preliminary design basis and to justify progression to site survey and detailed engineering. It is not sufficient to justify construction without further verification.

12.2 Answer to Research Questions

RQ1: What level and pattern of electricity demand is supported by the available evidence?

The seven-hospital portfolio demonstrates substantial variation in daily electricity demand. Rangala provides the most complete detailed evidence and has a screening demand of approximately 50.73 kWh/day. However, the completeness of the evidence varies between hospitals, meaning that portfolio comparisons should be interpreted as screening results rather than equivalent measured load profiles.

RQ2: What preliminary photovoltaic capacity is indicated?

The preliminary energy-balance method indicates different PV capacities according to hospital demand and site-specific solar productivity. For Rangala, the calculated capacity is approximately 11.76–11.83 kWp, while the latest project concept specifies 12.4 kWp. This confirms the approximate scale of the preliminary concept but does not establish the final engineering capacity.

RQ3: How closely do bill-based and equipment-based demand estimates agree?

The bill-based estimate provides the strongest available evidence of historical electricity purchase, while the bottom-up equipment model provides information about the composition and timing of demand. Their difference should be quantified using the validated equipment inventory. Any significant divergence should be treated as evidence of uncertainty requiring additional measurement rather than resolved through arbitrary adjustment.

RQ4: Which assumptions most strongly affect PV-BESS requirements?

The most important uncertainties are expected to include actual electricity demand, critical-load demand, photovoltaic productivity, self-consumption, battery autonomy, battery usable capacity, load growth and installed system cost. These parameters should be tested through sensitivity analysis before final design selection.

RQ5: What conditions are required for PV-BESS support during outages?

Resilience requires a defined critical-load panel, verified electrical separation from the utility supply, sufficient inverter power, sufficient usable battery energy, appropriate minimum state-of-charge settings, compatible generator integration and tested islanding and restoration procedures. A PV-BESS system should therefore not be described as providing complete hospital backup unless these conditions have been demonstrated.

RQ6: What information is required before implementation?

Progression to detailed engineering requires, at minimum, a site survey, three-phase load measurements, verified critical-load schedule, outage records, generator operating information, roof and structural assessment, electrical single-line verification, protection coordination, final string calculations, confirmed equipment schedules, supplier quotations and applicable regulatory approvals.

12.3 Technical Recommendations

The following actions are recommended before procurement:

- Retain 12.4 kWp only as the preliminary reference configuration until the final demand and site survey are completed.
- Install three-phase interval monitoring for at least one representative week and preferably longer, including representative high- and low-demand periods.
- Define and measure the essential hospital loads that must remain operational during grid interruptions.
- Determine battery capacity from the measured critical-load profile and required autonomy rather than from total daily hospital energy consumption.
- Resolve all differences between the 9.84, 11.83/12, 12.4 and 13.63 kWp design variants.

- Resolve the 20, 24 and 50 kWh battery variants through a formal autonomy and state-of-charge analysis.
- Issue one controlled single-line diagram showing the grid, generator, PV, battery, inverter, protection equipment and backed-up loads.
- Rerun all PV string and MPPT calculations using the final module datasheet and verified temperature range.
- Complete structural, shading, cable-route, switchboard, earthing and generator-interface surveys.
- Complete protection coordination and commissioning requirements before energization.

12.4 Economic and Environmental Recommendations

The incomplete preliminary budget should be replaced by comparable supplier quotations based on the corrected equipment schedule and single-line diagram. All quotations should distinguish equipment, transport, installation, taxes, commissioning, training, warranties, spare parts and exclusions.

Economic analysis should compare at least three configurations: PV-focused energy-cost reduction, balanced PV-BESS operation and resilience-priority operation. Battery replacement, PV degradation, operation and maintenance, tariff changes and self-consumption should be included in lifecycle analysis.

Environmental benefits should be calculated using verified emission factors and the expected amount of PV energy that actually displaces grid electricity or diesel generation. Under a zero-export operating strategy, total PV generation should not automatically be treated as avoided grid electricity.

12.5. Strategic and Research Recommendations

Rangala should be considered a methodological pilot rather than a configuration that can be copied directly to the remaining hospitals. Following implementation, at least twelve months of monitoring should be used to compare predicted and observed PV production, grid import, battery cycling, outage support, maintenance events and system availability.

The resulting evidence should be used to refine the assessment methodology for the remaining hospitals.

Future research should focus on:

- hourly or sub-hourly PV-BESS optimization using measured hospital load data;
- quantitative evaluation of outage frequency and duration;
- critical-load resilience metrics;
- comparison of AC- and DC-coupled architectures;
- lifecycle techno-economic optimization;
- uncertainty and sensitivity analysis;
- portfolio-level procurement and maintenance strategies; and
- long-term performance evaluation of PV-BESS systems in rural healthcare facilities.

12.6. Final Conclusion

The study demonstrates that photovoltaic and battery-storage systems can be assessed at preliminary level even when healthcare project information is incomplete, provided that evidence, assumptions and uncertainties are explicitly separated.

For the Rangala case, the available evidence supports a preliminary PV reference capacity of approximately 12 kWp, represented in the latest project concept by a 12.4 kWp array. However, the evidence does not establish that this configuration is optimal or construction-ready. In particular, the critical-load profile, battery autonomy, roof condition, electrical protection, generator interaction, final string configuration and project cost remain to be verified.

The principal contribution of the study is therefore not a final equipment selection but a traceable decision framework connecting field evidence to preliminary energy sizing, technical architecture, resilience requirements, economic considerations and implementation controls.

The appropriate next step is consequently progression to detailed engineering under defined decision gates. This approach preserves the value of the preliminary design while preventing incomplete information from being presented as engineering certainty.

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APPENDIX A – PROJECT DATA INVENTORY

File	Primary use in thesis	Quality note
1004 Rangala Preliminary Budget.xlsx	Cost categories, component options and preliminary prices	Summary contains broken references
1004 Rangala Request of Quotation 12kW.docx	Material and installation scope	Contains copied quantities requiring correction
1004 Victron String Design Tool.xlsm	MPPT/string compatibility	Must be rerun for final module
1004 Consumption and PV Power Assessment.xlsx	Load profile, bills, PV and battery simulation	Most complete analytical source
1004 Strings Check FV SmartSolars.xlsm	Second string-check variant	Configuration differs from latest BOM
1004 system architecture 12kWp.svg	Functional design concept	Validate against final single-line
MLT Project S4A.xlsx	Seven-hospital comparison	Screening-level data
PV SOLAR SYSTEM PROJECT.pptx	Objectives, methodology and programme narrative	Summary presentation

APPENDIX B – RANGALA BILL DATA

Month 2025	Days	Amount paid (KSh)	Derived average (kWh/day)
January	31	0	0.00
February	28	104,577	129.27
March	31	49,098	54.82
April	30	46,116	53.20
May	31	50,694	56.60
June	30	44,763	51.64
July	31	47,691	53.25
August	31	56,739	63.35
September	30	40,098	46.26
October	31	20,809	23.23
November	30	25,974	29.97
December	31	44,510	49.69

January contains no usable energy value. Energy was derived in the project workbook using currency conversion and an assumed €0.19/kWh average tariff.

APPENDIX C – LATEST PRELIMINARY COMPONENT SCHEDULE

Article	Description	Quantity	Design note
PV modules	Jinko 620 W bifacial N-type	20	12.4 kWp total
MPPT controllers	SmartSolar MPPT RS 450/100 VE.Can	2	Final string split required
Hybrid inverters	Victron MultiPlus-II 48/5000/70-50	3	Indicative three-phase arrangement
Grid-tied inverter	Fronius Symo 10.0-3-M	1	Clarify AC-coupled role
Battery modules	BYD Battery-Box LV Flex 6 kWh	4	24 kWh nominal
Battery management unit	BYD LV BMU	1	Compatibility to be confirmed
Monitoring	Cerbo GX + GX Touch	1 each	Remote monitoring
Energy meter	Victron-compatible three-phase meter	1	Zero-feed-in control
AC distribution board	Breakers and protection	1	Detailed schedule required
DC combiner/isolation	PV protection and combining	1 set	Detailed schedule required
Battery rack/cabinet	For BYD modules	1	Ventilation and access
Earthing system	Rods, clamps and conductors	1 set	Test and coordinate with existing earth

APPENDIX D – RFQ INSTALLATION SCOPE

- Transport all equipment to the verified Rangala site.
- Install roof-parallel module support structures following structural approval.
- Install and wire photovoltaic modules and connectors.
- Install and wire technical-room equipment, switchboards, inverters and meters.
- Reorganize radiology distribution wiring and install the new distribution board.
- Install conduits and underground channels, including excavation and reinstatement.
- Extend and test the grounding system.
- Configure zero feed-in, start-up, monitoring and functional tests.
- Provide two full days of on-site testing, training and follow-up.