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MASTER OF SCIENCE IN RENEWABLE ENERGY COHORT 5

TECHNO-ECONOMIC ANALYSIS OF INTEGRATING SOLAR PV SYSTEMS INTO OFF-GRID TELECOM TOWERS IN RWANDA.

Case study: **KARONGI-MURUNDI KTRN Telecom Tower.**

Research thesis done and submitted by

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DECLARATION

I, Samuel NKURIKIYIMANA, declare that this research thesis is my original work, and has not been presented for a degree in the University of Rwanda or any other universities. All sources of materials used in work have been fully acknowledged in the correct academic format.

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DEDICATION

This work is dedicated to my family, friends, lectures and my classmates for the support and moral guidance provided to me while doing this thesis.

ACKNOWLEDGEMENTS

I would like to extend my heartfelt gratitude to everyone who supported me throughout this long and rewarding journey of studying. First and foremost, I express my sincere thanks to my family for their unwavering encouragement and belief in my abilities. I am deeply grateful to my lecturers, particularly Dr. Innocent NKURIKIYIMFURA, Dr. Maxime BINAMA, Dr. Eustache, Dr. Venant Kayibanda, Dr. Ruganzu, and Dr. Alice, for their invaluable guidance and the comfort they provided during my master's courses and the thesis work. Their mentorship played a pivotal role in shaping my academic and personal growth. I would also like to acknowledge the University of Rwanda for the tremendous support and resources provided during my studies, which significantly contributed to my success. Finally, I extend my appreciation to my classmates for their collaboration, insightful ideas, and unwavering support. Their camaraderie made this journey not only productive but also enjoyable.

ABSTRACT

The rapid growth of Rwanda's telecommunication infrastructure has created a greater demand for reliable and cost-effective energy solutions, particularly for off-grid telecom towers. Many of these sites still depend on diesel generators, which come with high fuel costs, significant carbon emissions, and ongoing maintenance challenges. This research investigates the techno-economic feasibility of integrating solar PV systems into off-grid telecom towers, using the Murundi KTRN Telecom Tower as a case study. The goal is to assess the potential of replacing diesel generators with a solar PV and battery storage system, focusing on its technical, economic, and environmental advantages.

To achieve this, the study employs hybrid research methodology, combining data collection, system modeling, and financial analysis. Key aspects such as load demand patterns, energy consumption, and diesel generator operating costs were analyzed to understand current power needs. The system was then simulated using PVsyst software, which provided insights into optimal system sizing, battery autonomy, inverter capacity, and overall efficiency. This approach ensures that the proposed solar PV solution is both technically sound and economically viable, offering a sustainable alternative for powering off-grid telecom infrastructure.

The findings demonstrate that a 30.2 kWp solar PV system with a 7400 Ah lithium-ion battery storage can effectively meet the telecom tower's energy demand, ensuring two days of autonomy and significantly reducing reliance on the backup generator. The system achieves a solar fraction of 78.08% and a performance ratio of 74.78%, indicating high operational efficiency. Financial analysis reveals an LCOE of \$0.16/kWh, a payback period of approximately two years, and an ROI of 1139.5%, making it a cost-effective alternative to diesel-powered systems. Furthermore, the system is projected to eliminate 132.6 million Rwandan francs in fuel costs over five years while significantly reducing CO_2 emissions.

The study concludes that integrating solar PV systems in off-grid telecom towers is both economically viable and environmentally sustainable. Future research should focus on battery storage optimization, hybrid renewable energy integration, and demand-side management strategies to further improve system efficiency and cost-effectiveness. The study's findings provide a scalable model for deploying renewable energy solutions in remote telecom infrastructure, supporting Rwanda's clean energy transition and sustainable development objectives.

Keywords: *Rural electrification, Renewable Energy, Off-grid PV Systems, Grid lines, solar home systems, mini-grid systems.*

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LIST OF ABBREVIATIONS

EDPRS	Economic Development and Poverty Reduction Strategy
GoR	Government of Rwanda
EICV3	Third Integrated Household Living Conditions Survey
ESMAP	Energy Sector Management Assistance Program
GHG	Greenhouse gases
PVGIS	Photovoltaic Geographical Information System
IRENA	International Renewable Energy Agency
NREL	National Renewable Energy Laboratory
NGOs	Non-Governmental Organizations
GlobHor|	Global horizontal irradiation
DiffHor	Horizontal diffuse irradiation
T_Amb	Ambient Temperature
GlobInc	Global incident in coll. plane
GlobEff	Effective Global, corr. for IAM and shadings
EArray	Effective energy at the output of the array
E_User	Energy supplied to the user
E_Solar	Energy from the sun
E_Grid	Energy injected into grid
EFrGrid	Energy from the grid
E_Avail	Available solar energy
SolFrac	Solar Fraction (E-used/E-load)
GlobInc	Global incident Irradiance
EArrMPP	Array virtual energy at MPP
PV	Photovoltaic
MPP	Maximum power point
MPPT	Maximum power point tracking
IPP	Independent power producer
GHI	Global Horizontal Irradiation
NPV	Net Present Value
IRR	Internal Rate of Return
LCOE	Levelized Cost Of Energy
BESS	Battery Energy Storage Sysytem
REG	Rwanda Energy Group
C&I	Commercial and Industrial

CHAPTER 1. INTRODUCTION

The telecommunications field is a critical driver of socio-economic development in Rwanda. Telecom towers form the backbone of the country's communication infrastructure, providing mobile networks and internet connectivity both in urban cities as well as remote areas. One of the major pains that these towers especially ones in off-grid though face is with power supply, which needs to be cost-effective on-demand and reliable.

Until now, off-grid telecom towers in Rwanda have typically used diesel generators to source the majority of their energy. Although diesel generators can deliver uninterrupted power in the fastest manner, there are many drawbacks. Diesel fuel is known to fluctuate wildly in price and can be one of the largest operating expenses. Furthermore, fossil fuels used cause environmental problems such as climate change and air pollution[1].

To address these challenges, there is a growing recognition of the potential benefits of integrating renewable energy sources into off-grid telecom towers. Renewable energy, such as solar photovoltaic (PV) systems or wind turbines, offers a sustainable and cost-effective alternative to diesel generators. By harnessing renewable energy, telecom towers can reduce their dependence on fossil fuels, minimize operational costs, and mitigate environmental impacts [2].

However, several factors need to be considered when implementing renewable energy solutions for off-grid telecom towers. These include the power consumption patterns of the towers, the availability of renewable energy resources in specific locations, the economic viability of renewable energy technologies, and the environmental implications of transitioning to renewable energy[3].

Therefore, this thesis proposal aims to explore the use of solar PV systems for cost optimization of power consumption and evaluate the environmental implications for off-grid telecom towers in Rwanda. By conducting a case study specifically a KT Rwanda Networks tower called KARONGI-MURUNDI LTE site located at -2.12890 29.55514 coordinates as off-grid tower. The research will assess the feasibility and potential benefits of solar energy integration. The findings will contribute to the knowledge base on renewable energy adoption in the telecommunications sector, particularly in the context of Rwanda's off-grid towers, and inform decision-making for sustainable and efficient power supply solutions for supporting the country's broader goals of sustainable development and clean energy transition.

1.2. Problem Statement

In Rwanda, telecom towers, particularly those located in off-grid areas, heavily rely on non-renewable energy sources, leading to high operational costs and significant environmental implications. Due to geographical limitations where telecom towers are installed, there is the unavailability of grid supply in some interior rural areas or grid supply is also not available properly in most rural areas across the country. To provide power for those towers, the diesel generators are very commonly used. Diesel generators have some common issues such as their high running cost, maintenance cost, noise, and air (SO, CO, and NO) pollution emitted to the environment[14].

These disadvantages are forcing the telecom companies to search for other alternatives for reducing the cost and pollution produced by the diesel generators. Renewable energy sources may be the best alternatives to overcome the effects of above discussed problems. Korea Telecom Rwanda Networks (KTRN) is one of telecom companies operating in Rwanda that is facing this issue. The company has a tower called KARONGI-MURUNDI located in Karongi District, Murundi sector, Nzaratsi cell with latitude of -2.12890 and longitude of 29.55514 where there is no access to grid power. The tower relies on diesel generator 24/7 as a single power source.

1.3. Main Objective

The main objective of this thesis proposal is to investigate the potential of renewable energy (solar) integration for cost optimization of power consumption and evaluate the environmental implications for KARONGI-MURUNDI off-grid telecom tower using diesel generator. To achieve this objective, the research will focus on Cost Optimization, Power Consumption Analysis, Economic Viability and Environmental Implications.

1.4. Specific Objectives

1. To assess the power consumption patterns and load profiles of KARONGI-MURUNDI off-grid telecom tower.
2. To design and size a PV system for KARONGI-MURUNDI.
3. To evaluate the economic and technical viability of integrating PV system technology.

1.5. Scope

The scope of this research on solar PV systems integration in off-grid telecom towers in Rwanda will not cover aspects related to grid-connected towers or other countries' telecom infrastructures. The scope is defined to provide in-depth insights and recommendations within the given context, aiming to contribute to the sustainable development and energy optimization of off-grid telecom towers in Rwanda specifically KARONGI-MURUNDI.

1.6. Significance of the study

This research holds significant importance in terms of energy access, economic viability, environmental sustainability, policy development, and the achievement of sustainable development goals. The outcomes can support informed decision-making and guide the transition to cleaner and more sustainable energy sources in the telecommunications sector, benefiting both the industry and the broader Rwandan society.

CHAPTER 2. LITERATURE REVIEW

2.1. Basic concepts

2.1.1. Telecommunication towers

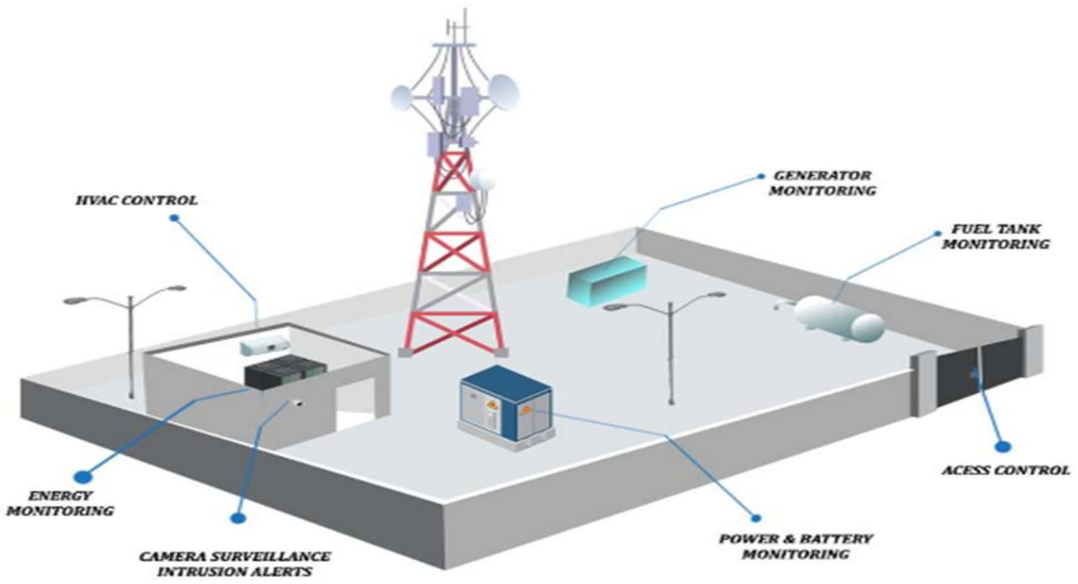


Figure 2-1: Components of a Telecom Tower

As per definition, Telecommunication towers include all types of structures that transmit any communication signal such as radio and TV broadcasting, emergency medical services (EMS), microwave, global positioning satellite (GPS), cellular phone antennas and internet. Usually, it's called a Base Transceiver Station (BTS)[1].

The rapid expansion of the telecommunications sector in Rwanda has led to the proliferation of telecom towers across the country, providing essential communication infrastructure to both urban and remote areas. However, powering these towers, especially those located in off-grid regions, poses significant challenges in terms of cost and environmental impact. Conventional energy sources, such as diesel generators, are commonly used to ensure uninterrupted power supply for these towers. However, the reliance on fossil fuels not only incurs high operational costs but also contributes to carbon emissions and environmental degradation[4].

To address these challenges, the implementation of renewable energy solutions has emerged as a promising approach. Renewable energy sources, such as solar and wind power, offer an alternative to conventional energy sources, offering the potential for cost optimization and reduced environmental impacts[5]. This research focuses on techno-economic and life cycle assessment of solar PV systems integration in off-grid telecom Towers in RWANDA. Keywords to consider in this research are:

2.1.2 Renewable Energy

Renewable energy refers to energy derived from sources that are naturally replenished, such as solar, wind, hydro, biomass, and geothermal energy. These sources have the advantage of being sustainable, abundant, and environmentally friendly compared to fossil fuels[6].

2.1.3 Off-Grid Telecom Towers

Off-grid telecom towers are those that are not connected to the main electricity grid. They are often located in remote areas where grid infrastructure is unavailable or unreliable, requiring alternative power supply solutions.

2.1.4 Cost Optimization

Cost optimization aims to minimize operational expenses and maximize efficiency while maintaining or improving service quality. In the context of telecom towers, cost optimization strategies involve identifying and implementing measures to reduce power consumption and associated costs.

2.1.5 Environmental Implications

Environmental implications refer to the impact of human activities on the natural environment. In the context of telecom towers, environmental implications include factors such as carbon emissions, air pollution, and the consumption of fossil fuels.

2.1.6 Hybrid Systems

Hybrid systems combine multiple energy sources, such as renewable energy and conventional generators, to provide a reliable and sustainable power supply. Hybrid systems are commonly used in off-grid telecom towers to leverage the benefits of renewable energy while ensuring continuous power availability.

2.1.7 Return on Investment (ROI)

ROI is a financial metric used to evaluate the profitability of an investment. In the context of renewable energy integration in telecom towers, ROI analysis assesses the financial returns and payback period associated with the initial investment in renewable energy systems[7].

2.2 Cost optimization strategies and environmental impact of renewable energy integration in telecom towers

In this section of the literature review, we will examine relevant studies and research that have explored related topics or addressed related aspects of renewable energy integration, cost optimization, and environmental implications in the context of telecom towers. These works provide insights into the existing knowledge and research gaps in the field.

Vikal et Al. have conducted a case study in India. By using Fuzzy AHP and TOPSIS approach, they concluded that integration of PV system is a reliable and sustainable solution for off grid telecom towers that have a single source of power as diesel generators[6]. Other researchers Badawe et Al. employed optimization methodology by using HOMER software, revealed that hybrid system by integration of renewable energy for powering remote telecom towers is a best solution[8][9]. Olabode et Al emphasized that to power remote locations including telecom towers by using hybrid power generation such as PV systems and diesel generator is a sustainable and reliable energy sources in developing countries[10].

Numerous researchers like M. T. Yeshalem et Al., D. E. Babatunde et Al. and O. J. Omodara also K. Janardhan et Al. investigated various cost optimization strategies for telecom towers, including load management techniques, energy efficiency measures and renewable energy integration. By using different tools as HOMER and Mathematical modeling they analyzed the potential cost savings and operational benefits achieved through these strategies, considering factors such as fuel costs, maintenance expenses and system upgrades. They concluded that integrated PV system in power generation system of rural telecom towers and remote location is more benefit than rely on diesel generator only [11][12][13][14].

According to Ali et Al., BTS located in remote regions, most of them rely on diesel generators as a common power supply solution. However, they contribute to high carbon emission. To reduce the quantity emission, integration of renewable energy can be a solution to energy problem. Various studies assessed the environmental implications of telecom towers, particularly in terms of carbon emissions and air pollution. They compared the environmental footprint of diesel generators versus renewable energy solutions, highlighting the potential for reducing greenhouse gas emissions and improving air quality through the adoption of renewable energy technologies like PV system[5][14].

Ud-Din Khan et Al. developed a study economic analysis of PV system powering a remote region for instance an off-grid telecom tower generally powered by a diesel generator. By using theoretical and computational models, the study concluded that the integrated PV system is the most feasible and economic[15]. The researchers conducted an economic analysis of renewable energy integration in telecom towers, considering the initial investment costs, ongoing maintenance expenses, and financial viability. They utilized financial models and return on investment calculations to evaluate the cost-effectiveness and long-term profitability of renewable energy solutions compared to traditional power sources[7][16].

Several case studies have been conducted in different regions, including developing countries, where renewable energy solutions were implemented in off-grid telecom towers. These case studies examined the technical feasibility, economic viability, and environmental impact of renewable energy integration, providing real-world examples and lessons learned[17][15][18][19]. Moreover, Syed et Al., based on the assessment conducted in Pakistan, they revealed that renewable energy especially PV system integrated in existing power system for remote telecom towers contributes more to reduce GHG emissions[20][21]. The previous works and studies related to renewable energy integration, cost optimization and environmental implications in telecom towers have contributed valuable insights to the field in different countries like India, Pakistan, South Africa Nepal, Canada and Nigeria. However, there are still several countries and areas that require further research depends on their geographical location. This research will focus on techno-economic and life cycle assessment of solar PV systems integration in off-grid Telecom Towers in RWANDA.

CHAPTER 3. METHODOLOGY

3.1 Introduction

The methodology employed in this study integrates quantitative analysis, economic evaluation and optimization techniques to assess the feasibility of transitioning the KARONGI-MURUNDI off-grid telecom tower from diesel dependence to a standalone solar photovoltaic (PV) system. The research approach is tailored to the specific environmental and operational conditions of Rwanda, ensuring that the proposed renewable energy solution is both technically and economically viable. Key aspects considered include power consumption patterns, energy demand forecasting, solar resource availability, system design, and cost-benefit analysis. To enhance accuracy, the study utilizes a combination of historical energy consumption records, real-time measurements, site surveys, and meteorological data from credible sources such as Meteo Rwanda and the National Solar Radiation Database (NSRDB).

The research methodology is structured into distinct phases to provide a systematic and data-driven evaluation. First, data collection involves assessing energy consumption trends, peak load demands, and diesel generator operational costs. Second, solar resource assessment is conducted to determine the feasibility of solar PV integration by analyzing site-specific irradiance levels and climatic conditions. Third, PV system design and component sizing are performed using established engineering principles and simulation tools, ensuring optimal performance and reliability. Finally, an economic and environmental impact analysis evaluates the financial feasibility and long-term benefits of solar integration, considering fuel savings, maintenance costs, carbon footprint reduction, and return on investment (ROI). By following this structured approach, the study provides actionable insights for implementing a sustainable and cost-effective renewable energy solution for off-grid telecom infrastructure in Rwanda.

3.2 Data collection

3.2.1 Power consumption patterns and load profiles of Karongi-Murundi off-grid telecom towers

This research involves the collection of relevant data from Karongi-Murundi off-grid telecom tower relies on diesel generator. This will include power consumption data, load profiles, and other relevant parameters such as tower location, tower specifications and historical fuel consumption data. In addition, on site measurements and questionnaires have been used. The collected data has been analyzed to assess the power consumption patterns and load profile of this off-grid telecom tower. Statistical analysis and data visualization techniques have been used to identify trends, peak demand periods and usage patterns.

3.2.1.1 Power consumption and load profile

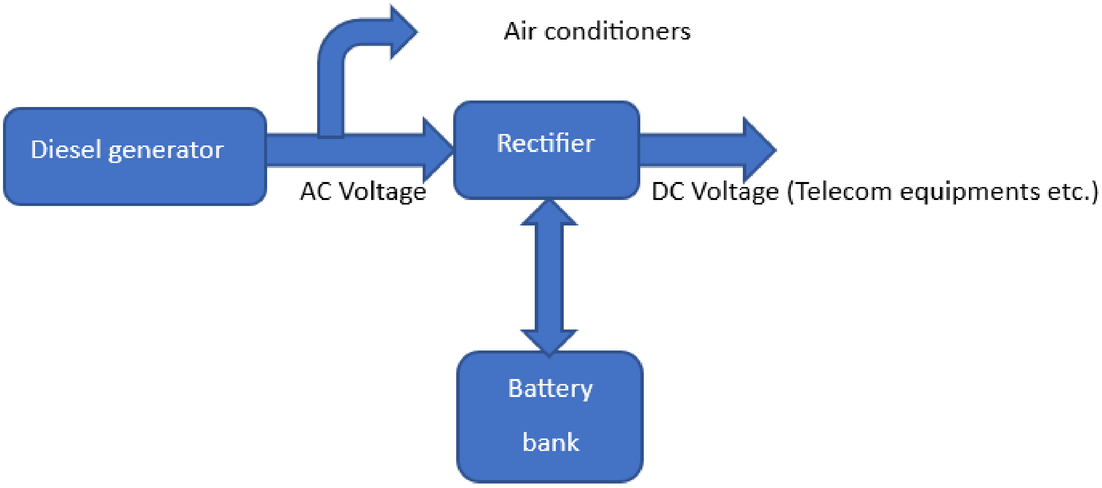


Figure 2:Existing scenario with Diesel generator

Components or devices that consume power found on this tower are the following:

Table 1: Tower power equipment and devices

#	Equipment/Device	Rated power (kW)	Qty of Equipment	System Voltage
1	Transmission Radios	0.8	3	48VDC
2	Transmission node digital unit	1	1	48VDC
3	Monitoring system	0.4	1	48VDC
4	LED Lighting lamps (Security light)	0.05	4	48VDC
5	Aviation light	0.1	1	48VDC
6	Air conditioners	1.2	2	220VAC
7	Diesel generator	30kVA	1	400/220VAC
8	Rectifier	9kW	1	220VAC-48VDC

Power generation and conversion equipment

- A 30kVA 230V 3 phase diesel generator
- A 9kW power rectifier 230VAC/48VDC 98% efficiency

A. BASE LOAD CALCULATION

To find out base or peak load, all equipment on the tower that need power to function has to be taken into consideration.

E=P*t

Where:

E: Energy consumption in kWh

P: Power in W

t: Operating time in hours

Table 2:Daily DC energy consumption

#	Equipment	Rated power (kW)	Qty of Equipment	Operating Hrs.	Total power (kW)	Energy consumption/Day (kWh)
1	Transmission Radios	0.8	3	24	2.4	57.6
2	Transmission node digital unit	1	1	24	1	24
3	Monitoring system	0.4	1	24	0.4	9.6
4	LED Lighting lamps (Security light)	0.05	4	24	0.2	4.8
5	Aviation light	0.1	1	24	0.1	2.4
Total DC Load					**4.1**	**98.4**

The above table 1 shows total daily DC energy consumption equal **98.4kWh/Day**

Table 3:Daily AC energy consumption

#	Equipment	Rated power (kW)	Qty of Equipment	Operating Hrs.	Total power(kW)	Energy consumption/Day(kWh)
1	Air conditioners	1.2	1	24	1.2	28.8

Table 2 shows daily AC energy consumption of **28.8 kWh/Day** for Air conditioner

By considering rectifier efficiency of 98% now total daily energy consumption can be determined.

$E_{\text{Total}} = E_{DC}/\eta_{\text{Rectifier}} + E_{AC}$

Total daily energy consumption=98.4 kWh/0.98 +28.8 kWh = **129.2 kWh/Day**

Power required=E_{Total}/24=129.2/24=**5.3kW**

Total monthly energy consumption= 129.2kWh*30=**3,876.2kWh**

Total yearly energy consumption= 129.2kWh*365=**47,158kWh**

B. PEAK LOAD CALCULATION

Note: All 2 air conditioners are working simultaneously specifically during summer season

Table 4: Peak load for AC power equipment

#	Equipment	Rated power (kW)	Qty of Equipment	Operating Hrs.	Total power(kW)	Energy consumption/Day(kWh)
1	Air conditioners	1.2	2	24	2.4	57.6

Table 4 demonstrates energy consumption for both 2 air conditioners

Total daily peak AC energy consumption = 98.4 kWh/0.98+57.6kWh=**158.4kWh/Day**

Power required=158.4/24=**6.6kW**

C. TOWER ENERGY CONSUMPTION

Table 5: Tower energy consumption

Power Required (W)	Operating time (Hrs)	E-Daily (kWh)	E-Monthly (kWh)	E-Yearly (kWh)
6.6	24	158.4	4,752	57,024

As shown in table 5, tower consumes 158.4kWh per day, 4,752 kWh per month and 57,024 kWh yearly.

3.2.1.2 Energy Source

This KARONGI-MURUNDI telecom tower has a single source of power which is a diesel generator that operates all 24 hours per day to avoid any network services interruption. A 30kVA diesel generator is used to power AC equipment (Air conditioners) and DC equipment via rectifier of 9kW. This Table 6 provides a clear and concise summary of the diesel generator's specifications and associated costs.

Table 6: specifications of Diesel generator at KARONGI-MURUNDI telecom tower

Specification	**Details**
Prime Power	30 Kva
Voltage	400 V (3 Phase)
Frequency	50 Hz
Power Factor	0.8
Fuel Type	Diesel
Measured Fuel Consumption per Hour (CPH)	1.73 L/h
Average Cost of Fuel	1,750 Rwf/L
Emission Factor for Diesel	2.68 kg CO_2/L
Genset Lifetime	43,800 run hours (≈ 5 years)
General Maintenance Interval	Every 200 run hours
Initial Cost (Purchase, Transport, Installation, Commissioning)	41,315,275 Rwf

3.2.1.3 Fuel Consumption and Maintenance Cost Analysis

As presented in Table 7 and Table 8 the diesel generator at the KARONGI-MURUNDI telecom tower consumes **41.52 liters of fuel daily**, leading to a **5-year fuel cost of 132.6 million RWF**

. Additionally, routine maintenance, performed every 200 hours, incurs a cost of **369,060 RWF per cycle**, totaling **80.8 million RWF** over the generator's lifetime. Combined, fuel and maintenance expenses result in an **operational cost of over 213.4 million RWF in 5 years**, highlighting the economic burden of diesel dependency and the potential cost savings from transitioning to renewable energy alternatives.

Table 7: Fuel Consumption and Cost

Period	Fuel Consumption (Liters)	Cost (Rwf)
Daily	41.52	-
Monthly	1,245.6	-
Yearly	15,154.8	-
5 Years	75,774	**132,604,500**

General maintenance and service of this diesel generator is done periodically after every 200 run hours by replacing engine oil, water & coolant, oil filter, fuel filter and air filter. Three consecutive times have been analyzed to get average cost of single general maintenance activity including transport fee and mission allowances.

Table 8: Maintenance Cost

Date	Maintenance Cost (Rwf)
August 5th, 2024	374,258
August 13th, 2024	361,045
August 22nd, 2024	371,877
Average Cost per Maintenance	**369,060**
Total Maintenance Cycles (5 Years)	**219**
Total Maintenance Cost (5 Years)	**80,824,140**

3.2.1.4 Repair and Replacement Cost

Based on records of last 3 years ago, **2,780,650 Rwf** including transport have been used for replacement of faulty engine starter batteries, electrical battery charger, Auto Transfer Switch (ATS), fuel solenoid and Alternator AVR Card.

Average Cost of Repair and replacement in 5 years= 2,780,650*5/3=**4,634,417Rwf**

3.2.1.5 End of Life Cost Diesel Generator

As recommended by manufacturers, a diesel generator has to be replaced by new one after 43,800 run hours of operation, almost 5 years. Telecommunication companies own off grid telecom towers rely only on this type of energy source have to comply with recommended standards by decommissioning the said above generator. End of life cost is composed by decommissioning, transportation, and disposal or recycling cost. The cost of last decommissioned generator in 2021 including transport was **650,000Rwf** and sold in auction at **504,000 Rwf**

Estimated cost saving at end of lifetime of generator is **500,000 Rwf**

3.2.2 Cost Analysis of Diesel Generator Power Generation for KARONGI-MURUNDI Telecom Tower

To determine the cost per kWh (RWF/kWh) for the diesel generator at the KARONGI-MURUNDI telecom tower, we will sum all running costs and divide them by the total energy produced over 5 years.

1. Total Running Cost

Table 9:Total Running Costs Over 5 Years

Cost of Component	Amount (RWF)
Fuel Cost	132,604,500
Maintenance Cost	80,824,140
Repair & Replacement Cost	4,634,417
Total Running Cost	218,062,957

Total Energy Generated Over 5 Years

- Daily energy consumption = 129.2 kWh/day
- Total energy in 5 years:

$$E_{\text{total}} = 129.2 \times 365 \times 5$$

$$E_{\text{total}} = 235{,}790 \text{ kWh}$$

2. Cost per kWh Calculation

$$\text{Cost per kWh} = \frac{\text{Total Running Cost (RWF)}}{\text{Total Energy (kWh)}}$$

$$\text{Cost per kWh} = \frac{218{,}062{,}957}{235{,}790}$$

$$\text{Cost per kWh} = 925 \text{ RWF/kWh}$$

The cost of 1 kWh from the diesel generator is approximately **925 RWF/kWh.**

This shows that diesel-based power generation is highly expensive, making the case for solar PV integration even stronger in reducing energy costs.

3.2.3 Solar Resources Assessment

According to Meteo Rwanda and National Solar Radiation Database (NSRDB) and geographical location of Karongi-Murundi tower at Latitude: -2.11 degrees and Longitude: 29.54 degrees, the following are the average data of mentioned above specific location.

- Latitude: -2.12890 degrees
- Longitude: 29.55514 degrees
- Elevation: 1919 meters
- Time zone: GMT+2

Irradiance

- Global horizontal: 4.61kWh/m^2/day
- Direct normal(Beam): 2.73 kWh/m^2/day
- Diffuse horizontal: 2.63 kWh/m^2/day
- Average temperature: 18.3°C
- Average wind speed: 2.1m/s
- Sun peak hours: 5hrs

CHAPTER 4. SIMULATION AND MODELING

Simulation and modelling of a PV system consider different parameters such PV module type, module orientation, shading and evaluating the performance of PV system.

4.1. Design Standalone Solar PV and Battery System for KARONGI-MURUNDI Off-Grid Telecom Tower

Basically, this tower uses both AC power to supply air conditioners and DC power for telecom equipment, lighting lamps etc. Air conditioners are connected to diesel generator directly while DC equipment are connected to it via rectifier that converts AC to DC. This study focuses on the replacement of existing system to solar PV system. This means, AC equipment will be powered from incorporated inverter.

Integration of PV system scenario

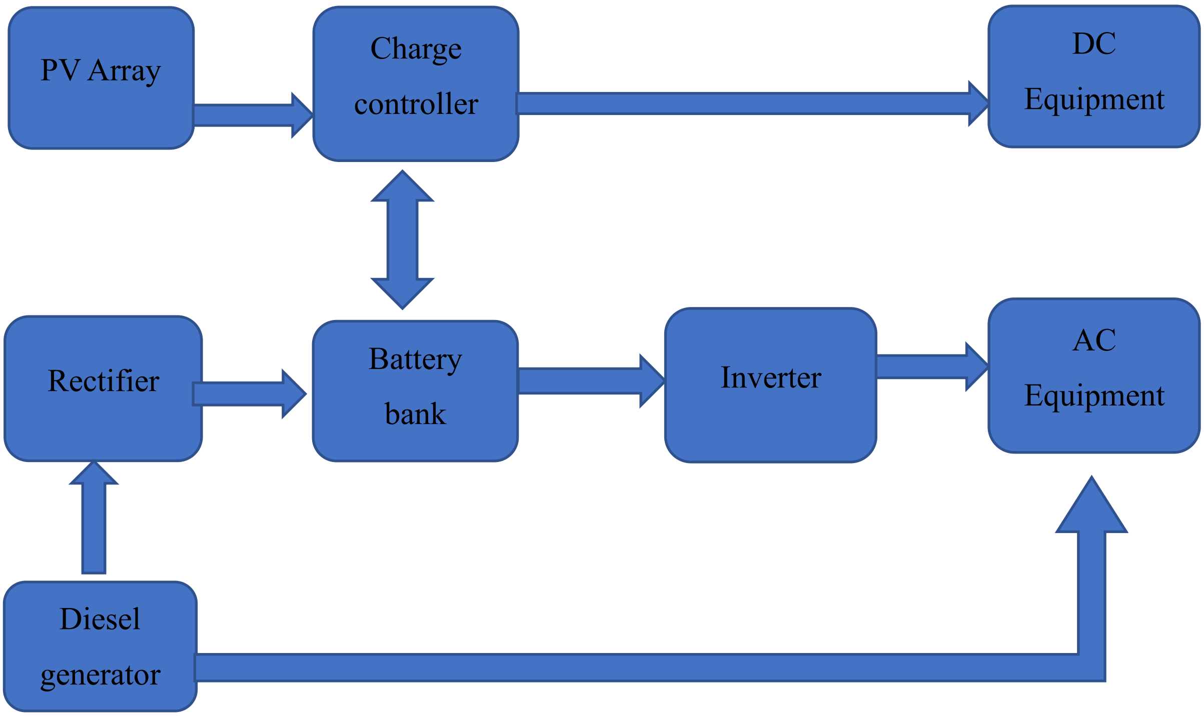


Figure 4-1: Block diagram of hybrid system

Since the KARONGI-MURUNDI telecom tower is off-grid, the PV system and battery bank must fully support its energy demand. Below is a detailed sizing based on power demand, peak demand, and energy storage for autonomy.

4.1.1 Load Demand Recap

Parameter	**Value**
Base Load Demand	5.3 kW
Peak Load Demand	6.6 kW
Daily Energy Demand	129.2 kWh
Peak Daily Energy Demand (Summer)	158.4 kWh
Required Autonomy	2 Days

4.1.2 The load profile

The load profile depicted in the Figure 4-1 represents the variation of power consumption over a 24-hour period, measured in kilowatts (kW). The curve indicates a general trend where demand starts at around 0.6 kW in the early hours, gradually decreases to its lowest point (approximately 0.4 kW) between 8 AM and 2 PM, and then steadily increases from mid-afternoon onward, peaking at around 0.7 kW in the evening (around 9-10 PM). This pattern suggests a typical residential or commercial load profile, where energy consumption is lower during working hours and increases in the evening due to increased appliance usage, lighting, and other energy-intensive activities.

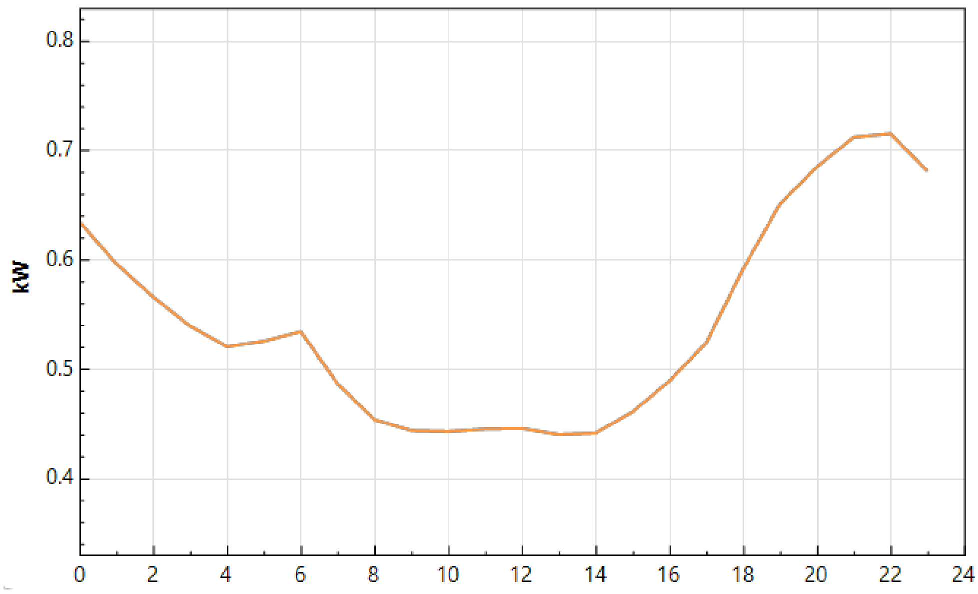


Figure 4-1: The load profile

4.1.3 Solar PV System Sizing

The PV system must generate enough energy to cover the daily load and recharge batteries within the available peak sunlight hours [22], [23], [24].

Step 1: Energy Required from PV System

To compensate for losses in the system (inverter, wiring, dust), a safety factor (SF) of 1.3 is applied.

$$E_{\mathrm{PV}} = \text{Daily Load} \times SF$$

$$E_{\mathrm{PV}} = 158.4 \times 1.3 = 206 \text{ kWh/day}$$

Step 2: PV Panel Capacity Calculation

From Meteo Rwanda and National Solar Radiation Database (NSRDB) data:

- Global Horizontal Irradiation (GHI) = 4.61 kWh/m²/day
- System Losses = 15% (0.85 efficiency)

$$P_{\mathrm{PV}} = \frac{E_{\mathrm{PV}}}{\mathrm{GHI} \times \text{Efficiency}}$$

$$P_{\mathrm{PV}} = \frac{206}{4.61 \times 0.85} = 52.5 \text{ kWp}$$

Step 3: Number of Solar Panels

Using **Trina Solar 670W panels (TSM-670DE21**):

$$N_{\text{panels}} = \frac{P_{\text{PV}}}{P_{\text{panel}}}$$

$$N_{\text{panels}} = \frac{52{,}500}{670} = 79 \text{ panels}$$

PV System Size = **79 × 670W panels (52.5 kWp total)**

4.1.4 Battery Storage Sizing

Since the tower is off grid, the battery system must provide power for 2 days of autonomy[2].

Step 1: Required Battery Capacity

Using:

- ☞ Autonomy Days = 2 days
- ☞ Depth of Discharge (DOD) = 80% (0.8)
- ☞ Battery Efficiency = 90% (0.9)
- ☞ System Voltage = 48V DC

$$E_{\text{Battery}} = \frac{\text{Daily Load} \times \text{Autonomy Days}}{\text{DOD} \times \text{Efficiency}}$$

$$E_{\text{Battery}} = \frac{158.4 \times 2}{0.8 \times 0.9}$$

$$E_{\text{Battery}} = \frac{316.8}{0.72} = 440 \text{ kWh}$$

Step 2: Battery Bank Configuration

Using 48V, 200Ah LiFePO4 batteries:

- Single battery capacity = 48V × 200Ah = 9.6 kWh
- Number of batteries required:

$$N_{\text{Batteries}} = \frac{E_{\text{Battery}}}{E_{\text{Battery, single}}}$$

$$N_{\text{Batteries}} = \frac{440}{9.6} = 46 \text{ batteries}$$

Battery Storage = **46 × 48V, 200Ah Lithium-Ion batteries (440 kWh total)**

4.1.5 Inverter and Charge Controller Sizing

Step 1: Inverter Selection

- The **peak AC load** is **6.5 kW**, but for reliability, we oversize by **20%**.

$$P_{\text{Inverter}} = P_{\text{Peak Load}} \times 1.2$$

$$P_{\text{Inverter}} = 6.5 \times 1.2 = 7.8 \text{ kW}$$

Recommended Inverter = **8 kW, 3-phase hybrid inverter (Huawei/Growatt)**

Step 2: Charge Controller Selection

The charge controller must handle the current from the PV array [27], [28], [29].

$$I_{\text{MPPT}} = \frac{P_{\text{PV}}}{V_{\text{System}}}$$

$$I_{\text{MPPT}} = \frac{52{,}500}{48} = 1{,}094A$$

Using 200A MPPT charge controllers:

$$N_{\text{Charge Controllers}} = \frac{I_{\text{MPPT}}}{200}$$

$$N_{\text{Charge Controllers}} = \frac{1{,}094}{200} = 6 \text{ controllers}$$

Recommended Charge Controllers are 6 each of **200A** MPPT charge controllers (Victron, SMA, Outback)

4.1.6 PV Array Area Calculation

Each Trina Solar TSM-670DE21 panel has:

- Dimensions = 2.38m × 1.30m
- Area per panel = 3.08 m²

$$A_{\text{PV Total}} = N_{\text{panels}} \times A_{\text{panel}}$$

$$A_{\text{PV Total}} = 79 \times 3.08 = 244 \text{ m}^2$$

Total PV Array Area ≈ 244 m²

(With spacing for maintenance, total installation area ≈ **350m²**.)

4.1.7 Design Summary of Standalone PV System

From the above calculation and summary in the Table 10 the 52.5 kWp standalone solar PV system with a 440 kWh battery bank and 8 kW hybrid inverter will fully replace the diesel generator, eliminating fuel costs (132.6M Rwf in 5 years), reducing CO_2 emissions, and lowering maintenance expenses. This system ensures 100% energy independence and is a cost-effective, sustainable solution for the KARONGI-MURUNDI telecom tower.

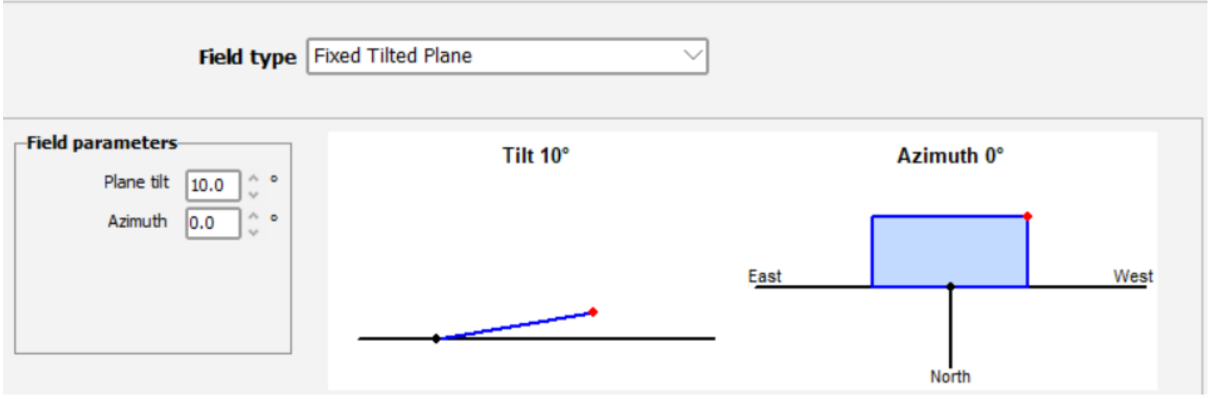
Table 10: Design Summary of Standalone PV System

Component	**Specification**	**Quantity**
PV Panels	670W Monocrystalline (Trina Solar TSM-670DE21)	79 panels
Total PV Power	52.5 kWp	-
Battery Storage	48V, 200Ah Lithium-Ion (LiFePO4)	46 units
Total Battery Capacity	440 kWh	-
Inverter	8 kW, 3-phase hybrid (Huawei/Growatt)	1 unit
Charge Controller	MPPT 200A (Victron/SMA)	6 units
PV Array Area	244 m² (with spacing ~350m²)	-

4.2 Modelling using simulation software

4.2.1. PV Module Orientation

The PV module orientation in Figure 4-2 is designed to optimize solar energy capture by aligning the panels at 10° tilt angle based on the site's geographical location. Given that the installation is in the southern hemisphere, the PV modules are likely oriented facing northward to maximize solar exposure throughout the day. This strategic orientation ensures that the system benefits from the highest possible irradiance levels, minimizing energy losses due to suboptimal positioning.



Field type: Fixed Tilted Plane

Field parameters

Plane tilt: 10.0 °

Azimuth: 0.0 °

Figure 4-2: PV Module Orientation

4.2.2. Perspective of the PV-field and surrounding shading scene

The modules are placed on a well-defined, green-shaded land area, which represents the designated field for solar installation, allowing for adequate spacing to prevent self-shading between rows and ensuring efficient energy generation.

The perspective of the PV field and surrounding shading scene confirms that the telecom tower does not pose a shading risk to the solar panels. This is because the site is located in the southern hemisphere, meaning that the sun's path remains predominantly in the northern sky. As a result, the tower, which is positioned to the south of the PV array, does not cast significant shadows on the solar panels, even during morning and late afternoon hours.

The adjacent building, which is divided into a powerhouse (housing inverters and battery storage) and a server room, is also placed in a manner that minimizes shading interference. This careful site planning ensures the PV system operates efficiently, maintaining high energy yields without disruption from surrounding structures.

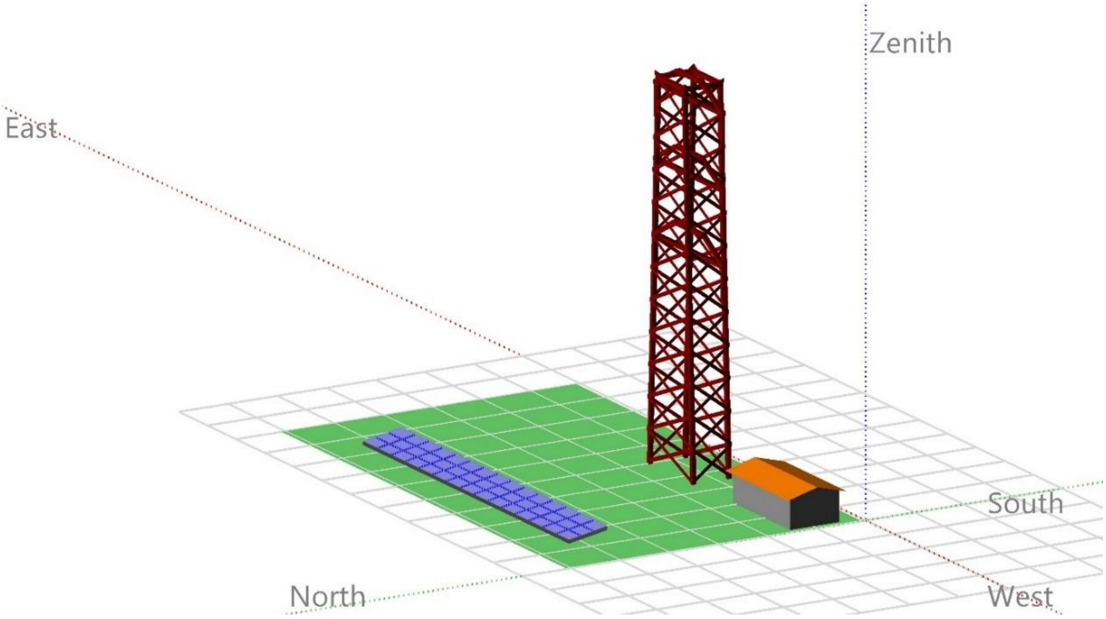


Figure 4-3: Perspective of the PV-field and surrounding shading scene

4.2.3 System design overview

The Table 11 presents the design of the standalone PV system with battery storage and a backup generator, designed to provide uninterrupted power to a telecom tower in Karongi-Murundi, Rwanda. The system ensures energy autonomy and reliability in off-grid conditions.

4.2.3.1 PV Array Configuration

From the Table 11, the system setup includes a PV module from CW Enerji (Model: CWT670-132PM12-V), which delivers a nominal power of 670 Wp per unit, with a total nominal capacity of 30.2 kWp under standard test conditions (STC). The system consists of 45 PV modules connected in 15 strings of 3 in series, operating at a maximum power point (MPPT) of 27.58 kWp, with an operating voltage of 104 V and a current of 264 A at 50°C. The total module area is 140 m², with a cell area of 131 m².

4.2.3.2 Battery Storage System

The energy storage system uses Huawei's Luna2000-10-SO lithium-ion batteries, connected in parallel with 37 units, providing a total stored energy of 319.7 kWh and a nominal capacity of 7400 Ah. The discharge limit is set to a minimum state of charge (SOC) of 10%.

The system is managed by Morningstar's GenStar GS MPPT 100M-48Vdc controller, which ensures a maximum efficiency of 98%.

4.2.3.3 Backup Generator Integration

For backup power, a 30kVA generator is used, with a nominal power of 24 kW and actual load demand power of 10 kW. This generator helps provide supplementary energy during periods of low solar and battery production or peak demand. Ensures power supply during prolonged low solar energy availability and works alongside battery storage to enhance system reliability.

Table 11: Modelled PV system

PV module	
Manufacturer	CW Enerji
Model	CWT670 - 132PM12 – V
(Original PVsyst database)	
Unit Nom. Power	670 Wp
Number of PV modules	45 units
Nominal (STC)	30.2 kWp
Modules	15 Strings x 3 In series
At operating cond. (50°C)	
Pmpp	27.58 kWp
U mpp	104 V
I mpp	264 A

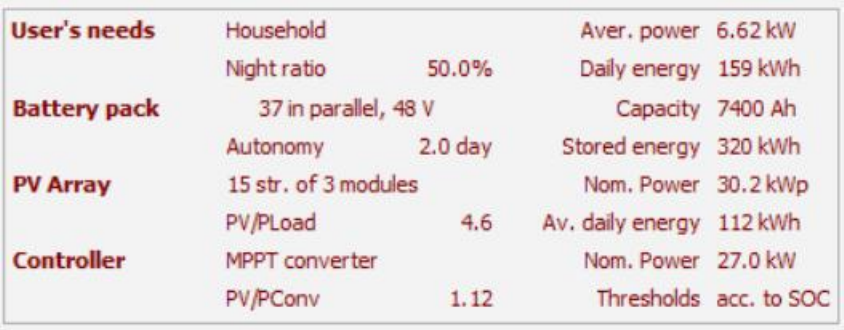
Battery	
Manufacturer	
Model	Luna2000-10-SO, with
Technology	Lithium-ion,
Nb. of units	37 in
Discharging min. SOC	10.0 %
Stored energy	319.7 kWh
Battery Pack Characteristics	
Voltage	48 V
Nominal Capacity	7400Ah
Temperature	External ambient temperature

Controller	
Manufacturer	Morningstar
Model	GenStar GS MPPT 100M-48Vdc
Nb. Units	5 units
Technology	MPPT converter
Temp coeff.	0.0 mV/°C/Elem.
Converter	
Maxi and EURO efficiencies	98.0 / 96.0 %

Battery Management control	
Threshold commands as	SOC calculation
Charging	SOC = 0.96 / 0.80
Discharging	SOC = 0.10 / 0.35
Back-Up Genset Command	SOC = 0.15/0.45

4.2.3.4 Load Requirements

The Figure 4-4 shows the telecom tower at Karongi-Murundi has an average power demand of 6.62 kW and a daily energy consumption of 159 kWh. With 50% of energy consumption occurring at night, the system heavily depends on battery storage to maintain continuous operation. This highlights the need for efficient battery management and sufficient storage capacity to ensure reliability during nighttime hours.



User's needs	Household		Aver. power	6.62 kW
	Night ratio	50.0%	Daily energy	159 kWh
Battery pack	37 in parallel, 48 V		Capacity	7400 Ah
	Autonomy	2.0 day	Stored energy	320 kWh
PV Array	15 str. of 3 modules		Nom. Power	30.2 kWp
	PV/PLoad	4.6	Av. daily energy	112 kWh
Controller	MPPT converter		Nom. Power	27.0 kW
	PV/PConv	1.12	Thresholds	acc. to SOC

Figure 4-4: Sized system

4.2.3.5 Performance & Efficiency Considerations

The PV/PLoad ratio of 4.6 indicates that the solar array is well-sized relative to the load, ensuring ample energy generation. The system’s nominal power of 30.2 kWp exceeds the required 27.0 kW, accounting for energy losses and inefficiencies. Additionally, battery State of Charge (SOC) thresholds are crucial for optimizing efficiency and extending battery lifespan, ensuring a balance between energy availability and battery longevity.

4.2.3.6 System Benefits

- ✓ **Energy Independence**: Reduces reliance on fossil fuels
- ✓ **Sustainable & Cost-Effective**: Utilizes solar energy for primary power supply
- ✓ **Reliable for Telecom Operations**: Ensures continuous uptime with **backup generator & battery storage**

4.2.3.7 Areas for Further Optimization

- ✓ Battery Sizing Validation: Assess if 2 days of autonomy is optimal for cost vs. reliability
- ✓ Load Profile Optimization: Evaluate energy efficiency measures to reduce nighttime consumption
- ✓ Hybrid System Control Strategy: Optimize generator runtime to reduce fuel costs

4.2.4 Designed Schematic Representation of Karongi-Murundi Off-Grid Telecom Tower Power System

This schematic (Figure 4-5) represents a standalone photovoltaic (PV) system designed to supply power to a telecom tower using solar energy, battery storage, and a backup generator. The **PV array** serves as the primary energy source, converting sunlight into electrical energy, which is regulated and distributed by the **charge controller (regulator)**. The generated power is either directly supplied to the load (user) or stored in **batteries** for later use. A **diode** prevents reverse current flow, ensuring efficient charging. The **charge controller** manages power flow, preventing battery overcharging and deep discharging, while also regulating voltage and current to protect system components.

When solar energy is insufficient, the system automatically switches to battery power to maintain a continuous power supply. If both the PV array and battery storage are unable to meet demand, a **backup generator** is activated to ensure reliability. The **fuse** and **temperature sensor** in the battery system provide additional safety measures by preventing overheating and electrical faults. This hybrid approach optimizes energy use, enhances system efficiency, and ensures uninterrupted operation of the telecom tower in off-grid locations like **Karongi-Murundi, Rwanda**.

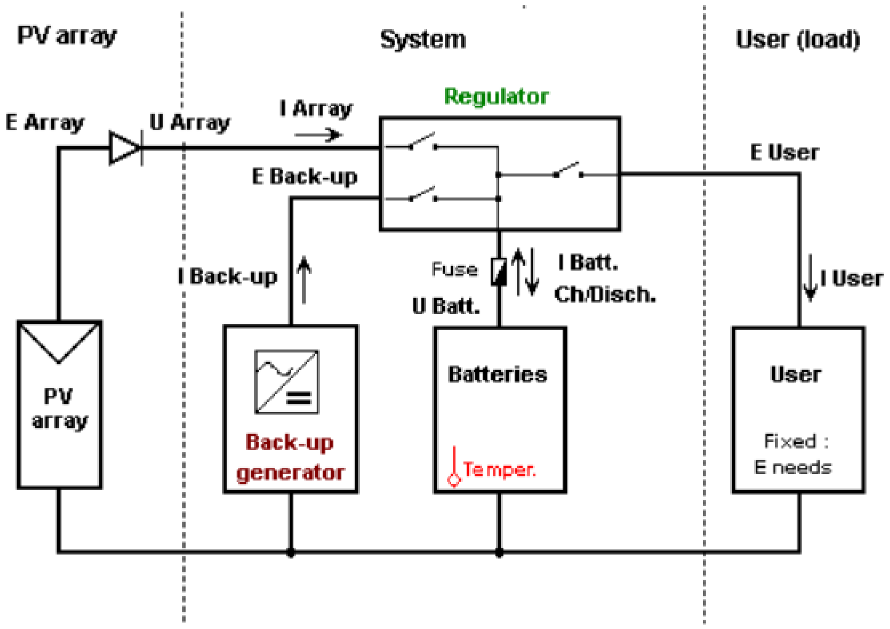


Figure 4-5: Designed schematic representation Karongi-Murundi off-grid telecom tower

4.2.5 Main Components & Explanation

This is a schematic diagram of a standalone PV system with battery storage and a backup generator, showing the energy flow and key components.

1. **PV Array (Photovoltaic Panels)**
   - Photovoltaic Panels convert solar energy into DC electricity.
   - Energy output is labeled **E Array**, voltage **U Array**, and current **I Array**.
   - A **diode** prevents reverse current flow from the batteries.

2. **Regulator (Charge Controller)**
    - Manages power distribution between the **batteries** and the **user (load)**.
    - Controls charging of the battery and prevents overcharging or deep discharging.
    - Switches between different power sources: PV, battery, or backup generator.
3. **Battery Storage System**
    - Stores excess solar energy for **nighttime or cloudy days**.
    - Monitored by **voltage (U Batt.)** and charge/discharge current **(I Batt. Ch/Disch.)**.
    - Includes a **fuse** for protection and a **temperature sensor** ("Temper.") to avoid overheating.
4. **Backup Generator**
    - Provides power when solar energy is insufficient, ensuring **continuous energy supply**.
    - Delivers energy (**E Back-up**) and current (**I Back-up**) when needed.
    - Works in coordination with the **regulator** and batteries.
5. **User (Load)**
    - Represents the **energy demand** of the telecom tower.
    - Requires **fixed power consumption (E User, I User)**.
    - Power is supplied from the **batteries** and **PV array**, with the generator as a last resort.

4.2.6 Power Flow Summary

1. Primary source: PV array generates power, supplying the user and charging the battery.
2. Battery discharge: When sunlight is insufficient, the battery supplies power to the load.
3. Backup generator: Activates when battery charge is too low to ensure uninterrupted power.

4.2.7 Key Takeaways

☞ Energy Independence – Ensures continuous operation off-grid.

☞ Hybrid Energy Management – Uses solar as primary, batteries as secondary, and a generator as backup.

☞ Protection Features – Includes fuses, temperature sensors, and a charge controller to prevent failures.

4.2.8 Discrepancy Between Calculated Values and Simulation Results

- The manual calculations provide a baseline but lack detailed loss factors, dynamic weather conditions, and real-time system interactions.
- PVsyst provides a more accurate, real-world estimation of energy yield, component performance, and battery behavior under varying conditions.
- By aligning calculations with IEEE/IEC standards and refining system inputs, the final design can minimize discrepancies and optimize performance for the Karongi-Murundi telecom tower project.

5.2 Technical Performance Analysis

5.2.1 Technical result

The Table 12 provides a monthly breakdown of solar energy generation, system efficiency, and energy utilization. The **Global Horizontal Irradiation (GlobHor)** represents the total solar radiation received per square meter, while the **Global Effective Irradiation (GlobEff)** accounts for the energy effectively utilized by the PV modules after considering tilt and shading effects. The system follows seasonal variations, with the highest energy availability (E_Avail) observed in July (4149 kWh) and the lowest in September (3806 kWh), aligning with variations in solar irradiation throughout the year.

The **energy consumption and solar fraction (SolFrac)** values indicate the system's ability to meet the energy demand. The highest solar fraction (0.811) occurs in July, demonstrating that the PV system efficiently meets demand with minimal reliance on alternative energy sources. Conversely, October, November, and December show the lowest solar fractions, around 0.726–0.739, implying increased dependency on stored energy or backup sources. The **E_Unused** column highlights minimal energy losses, meaning that most generated energy is effectively utilized. The annual summary confirms an **energy availability of 46,703 kWh**, with **57,976 kWh consumed**, leading to an average solar fraction of **0.781**, indicating a well-balanced system design.

Table 12: Analysis of Solar Energy Generation, Storage, and Consumption Patterns

	GlobHor kWh/m^2	**GlobEff** kWh/m^2	**E_Avail** kWh	**EUnused** kWh	**E_User** kWh	**E_Load** kWh	**SolFrac** ratio
January	181.8	155.2	3953	0.00	492	4924	0.786
February	163.1	143.9	3637	0.12	444	4447	0.796
March	176.4	161.5	4073	0.13	492	4924	0.804
April	164.6	155.7	3949	0.24	476	4765	0.790
May	164.4	157.9	4004	0.63	492	4924	0.803
June	157.1	154.5	3925	0.27	476	4765	0.800
July	167.5	163.4	4149	0.00	492	4924	0.811
August	168.0	160.5	4063	0.00	492	4924	0.789
September	162.2	150.8	3806	0.52	476	4765	0.786
October	164.5	146.7	3695	0.00	492	4924	0.726
November	167.5	144.1	3691	0.40	476	4765	0.740
December	175.5	147.4	3757	0.26	492	4924	0.739
Year	2012.5	1841.6	46703	2.609	57976	57974	0.781

Legends

GlobHor	Global horizontal irradiation	E_Load	Energy need of the user (Load)
GlobEff	Effective Global, corr. for IAM and shadings	SolFrac	Solar fraction (EUsed / ELoad)
E_Avail	Available Solar Energy		
EUnused	Unused energy (battery full)		

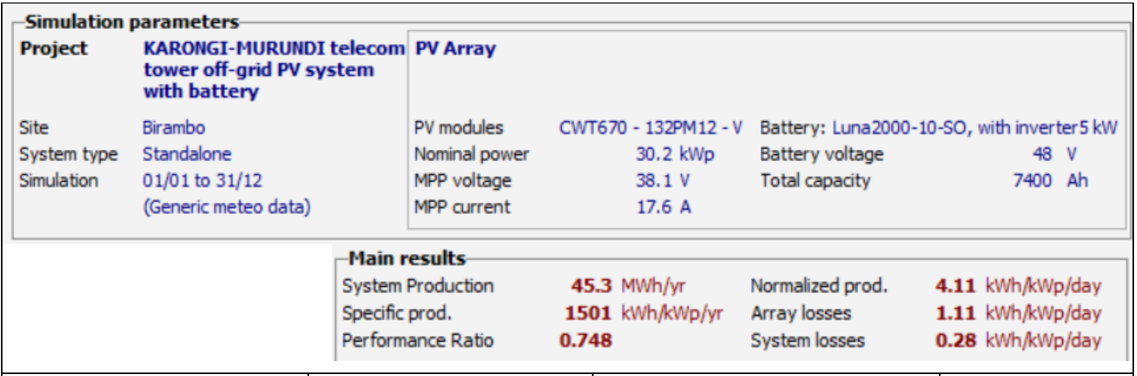
E_User	Energy supplied to the user

5.2.2 System Production Evaluation

As demonstrated in the main result Table 13, the useful energy from solar is **57,976 kWh per year**, demonstrating that the PV system is capable of covering a significant portion of the energy demand. The **Performance Ratio (PR)** of **74.78%** indicates an efficient system, accounting for losses due to temperature, system inefficiencies, and other operational constraints. The **available solar energy** reaching the PV array is **46,703 kWh per year**, leading to a **Solar Fraction (SF)** of **78.08%**, meaning that nearly **78% of the total energy demand is covered by solar power**.

Despite the high solar contribution, there is still a need for a **backup energy source**, with the generator supplying **12,711 kWh per year** and consuming **763 liters of fuel annually**. The **battery system is performing well**, with a **State of Wear (SOW) of 97.9% based on cycles**, indicating that the battery is in good condition with minimal degradation. The **static SOW is 90.5%**, suggesting that while the battery is aging, it remains within acceptable performance limits. With only **3 kWh of excess (unused) energy per year**, the system is well-sized to match demand, ensuring minimal energy wastage.

Table 13: Main results



Simulation parameters

Project	**KARONGI-MURUNDI telecom tower off-grid PV system with battery**	**PV Array**			
Site	Birambo	PV modules	CWT670 - 132PM12 - V	Battery:	Luna2000-10-SO, with inverter5 kW
System type	Standalone	Nominal power	30.2 kWp	Battery voltage	48 V
Simulation	01/01 to 31/12 (Generic meteo data)	MPP voltage	38.1 V	Total capacity	7400 Ah
		MPP current	17.6 A		

Main results

System Production	**45.3** MWh/yr	Normalized prod.	**4.11** kWh/kWp/day
Specific prod.	**1501** kWh/kWp/yr	Array losses	**1.11** kWh/kWp/day
Performance Ratio	**0.748**	System losses	**0.28** kWh/kWp/day

System Production Useful energy from solar	57976 kWh/year	Perf. Ratio PR	74.78 %
Available solar energy	46703 kWh/year	Solar Fraction SF	78.08 %
Excess (unused)	3 kWh/year		
Back-Up energy from generator Back-Up energy	12711 kWh/year	**Battery aging (State of Wear)** Cycles SOW	97.9 %
Fuel Consumption	763 liter/year	Static SOW	90.5 %

5.2.3 Normalized production analysis

The Figure 0-1 visually represents the distribution of solar energy usage and losses throughout the year. The key observations are:

- **Energy Supplied to the User (Yf - Brown Section):** This constitutes **74.8%** of the total production, showing that a significant portion of the generated energy is effectively utilized.
- **System Losses and Battery Charging (Ls - Green Section): 5.1%** of the energy is lost due to system inefficiencies and battery charging processes.
- **Collection Loss (Lc - Purple Section): 20.1%** of energy is lost in the PV array due to various factors like shading, soiling, and module inefficiencies.
- **Unused Energy (Lu - Blue Section): 0%**, indicating that all excess energy is either stored or used, with no significant curtailment.

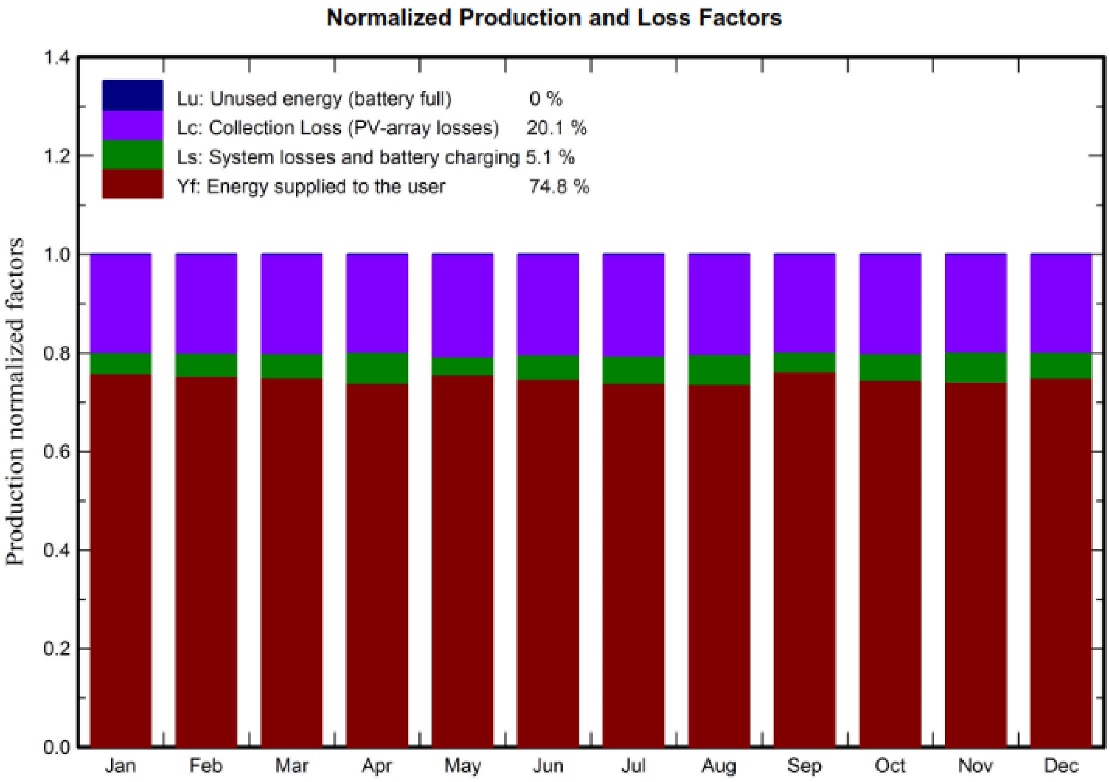


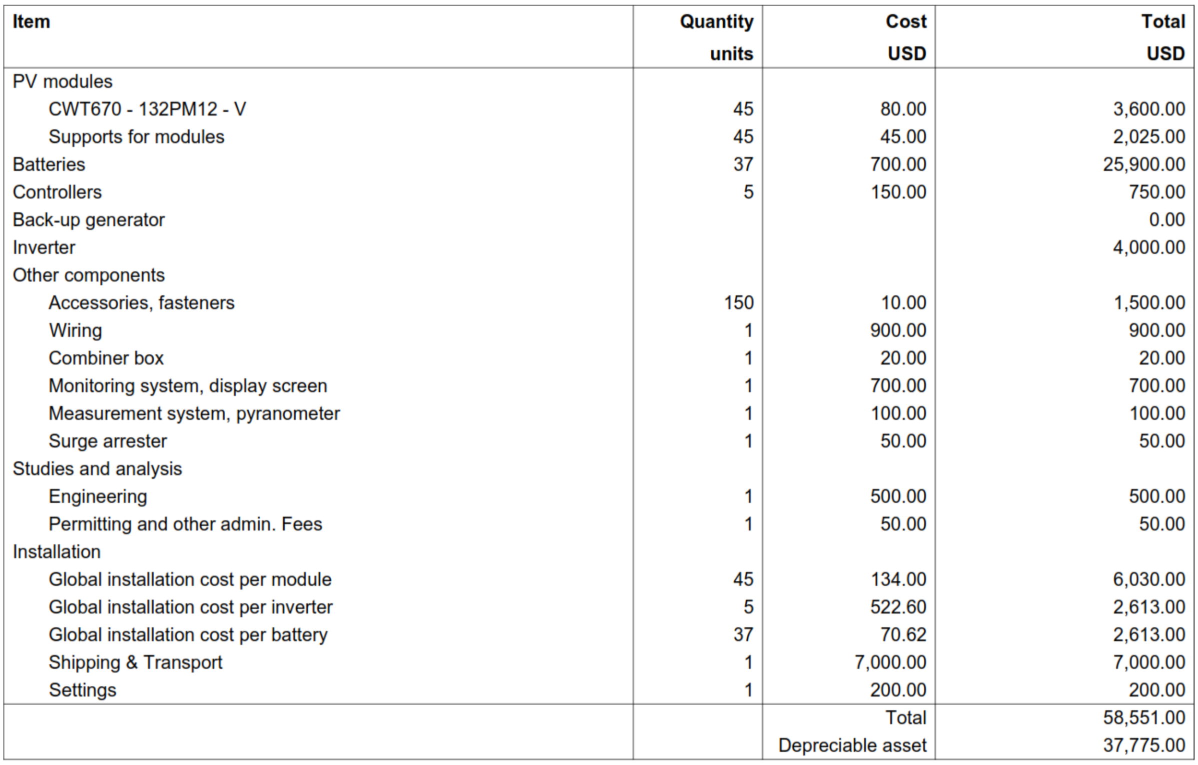
Figure 0-1: Normalized Production and Loss Factors

5.3 Financial analysis

5.3.1 The investment analysis

The PV system investment of $58,551 covers 45 PV modules (CWT670 - 132PM12 - V), 37 batteries, 5 controllers, 1 inverter, and essential infrastructure such as mounting structures, wiring, and monitoring systems as shown the Table 14. Additional costs include engineering studies, permitting, installation, and shipping to ensure optimal performance. With $37,775 classified as depreciable assets, the financial plan emphasizes long-term sustainability, cost-effectiveness, and reliable energy production with integrated backup power.

Table 14: Cost of the system



Item	Quantity units	Cost USD	Total USD
PV modules			
CWT670 - 132PM12 - V	45	80.00	3,600.00
Supports for modules	45	45.00	2,025.00
Batteries	37	700.00	25,900.00
Controllers	5	150.00	750.00
Back-up generator			0.00
Inverter			4,000.00
Other components			
Accessories, fasteners	150	10.00	1,500.00
Wiring	1	900.00	900.00
Combiner box	1	20.00	20.00
Monitoring system, display screen	1	700.00	700.00
Measurement system, pyranometer	1	100.00	100.00
Surge arrester	1	50.00	50.00
Studies and analysis			
Engineering	1	500.00	500.00
Permitting and other admin. Fees	1	50.00	50.00
Installation			
Global installation cost per module	45	134.00	6,030.00
Global installation cost per inverter	5	522.60	2,613.00
Global installation cost per battery	37	70.62	2,613.00
Shipping & Transport	1	7,000.00	7,000.00
Settings	1	200.00	200.00
		Total	58,551.00
		Depreciable asset	37,775.00

5.3.2 Annual operational costs (OPEX)

The annual operational costs (OPEX) Table 15 for the PV system total USD 9,234.02. This includes various components such as salaries for personnel involved in system maintenance and operations, which amount to USD 2,000.00. Regular repairs and cleaning contribute USD 1,000.00 each, ensuring the system operates efficiently. A provision for battery replacement is set at USD 2,590.00, covering future replacements as needed. A security fund of USD 1,500.00 is allocated to safeguard the system, while USD 1,144.02 is dedicated to fuel for the backup generator to maintain power during outages. These costs ensure the system's continued operation, reliability, and longevity.

Table 15: Annual operational costs

Item	**Total USD/year**
Maintenance	
Salaries	2,000.00
Repairs	1,000.00
Cleaning	1,000.00
Provision for battery replacement	2,590.00
Security fund	1,500.00
Fuel for Back-Up generator	1,144.02
Total (OPEX)	9,234.02

5.3.3 Strategic approach to long-term financial planning and sustainability for the PV system

The depreciation Table 16 reflects a strategic approach to long-term financial planning and sustainability for the PV system. By applying the straight-line depreciation method over extended periods, typically 20 to 25 years, the table ensures that the asset values are gradually written off, aligning with their useful lifespans. This approach helps in accurately predicting future expenses and maintaining a clear financial outlook. For instance, the total depreciable value of assets like the PV modules, batteries, and inverter sums up to USD 37,775.00, contributing to effective budget allocation for maintenance, replacements, and upgrades. The zero salvage value for most components underscores a focus on their complete use until the end of their life cycle, ensuring financial resources are appropriately managed for system sustainability.

Table 16: Depreciable assets

Asset	**method**	**Depreciation Period (years)**	**Salvage value (USD) (USD)**	**Depreciable (USD)**
PV modules				
CWT670 - 132PM12 – V	Straight-line	25	0.00	3,600.00
Supports for modules	Straight-line	25	0.00	2,025.00
Batteries	Straight-line	10	0.00	25,900.00
Controllers	Straight-line	25	0.00	750.00
Back-up generator	Straight-line	25	0.00	0.00
Inverter	Straight-line	20	0.00	4,000.00
Accessories, fasteners	Straight-line	20	0.00	1,500.00
		Total	**0.00**	**37,775.00**

5.3.4 Cumulative cash flow analysis and financial overview of a project over a 25-year period

The Figure 0-2 visualizes the financial progression of the project over a 25-year period. It shows the cumulative profit, electricity sale, own funds, running costs, and depreciation allowance. The cumulative profit steadily increases over time, indicating the profitability of the project after an initial investment. The electricity sale and running costs remain constant throughout the years, while the depreciation allowance decreases in later years. This graph provides a clear view of the project's financial performance, demonstrating its growing profitability with time.

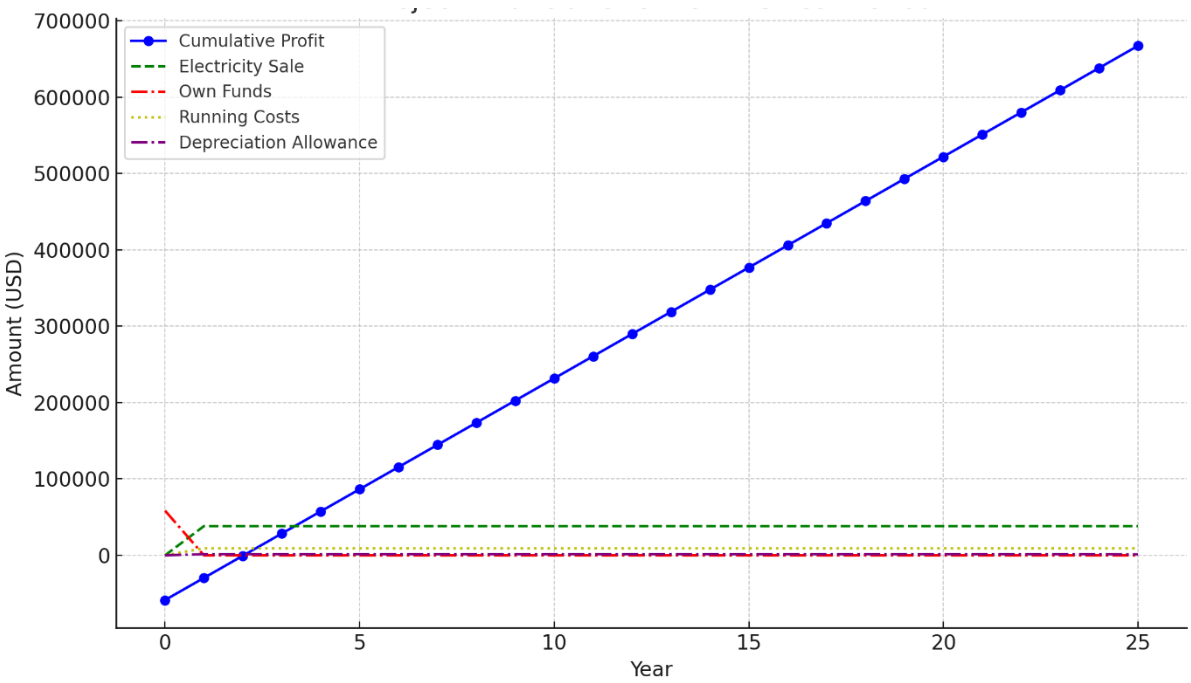


Figure 0-2: financial overview of a project over a 25-year period

The Figure 0-2 provides a financial overview of a project over a 25-year period, illustrating the relationship between electricity sales, operating costs, depreciation allowances, taxable income, taxes, and profits. In the initial year (Year 0), the installation cost is entirely funded by own funds, resulting in a negative cumulative profit of -58,551 USD. By Year 1, the project starts generating a significant after-tax profit of 29,030 USD, reducing the cumulative loss.

From Year 3 onward, the cumulative profit becomes positive, and by Year 25, it reaches a total of 667,199 USD, yielding a cumulative return on investment of 1239.5%. Throughout the period, the project maintains a steady annual income from electricity sales of 38,264 USD, while operating costs remain consistent. The total accumulated profit at the end of Year 25 significantly surpasses the initial investment, indicating a highly successful financial return over the project's lifespan.

5.3.5 The income allocation

The largest segment of the pie chart (Figure 0-3) is green and represents the net profit at 75.87% of total income. This substantial proportion indicates that after accounting for all operational expenses, over three-quarters of the income generated remains as profit, demonstrating the strong economic performance of the solar PV system.

The second largest segment is colored dark blue and represents maintenance costs at 21.14% of total income. This includes the various operational expenditures outlined in the report such as routine maintenance, salaries, repairs, cleaning, and provisions for battery replacement and security. While significant, these costs are well-balanced against the project's income.

The smallest segment is orange and shows fuel costs for the backup generator at only 2.99% of income. This minimal proportion reflects the high solar fraction (78.08%) of the system, meaning the backup generator runs infrequently, which not only reduces operational costs but also minimizes the carbon footprint of the installation.

The Figure 0-3 effectively illustrates how the KARONGI-MURUNDI telecom tower project allocates its resources efficiently, with the vast majority of income translating to profit rather than being consumed by operational expenses, which supports the favorable financial metrics including the 2-year payback period and 49.58% IRR.

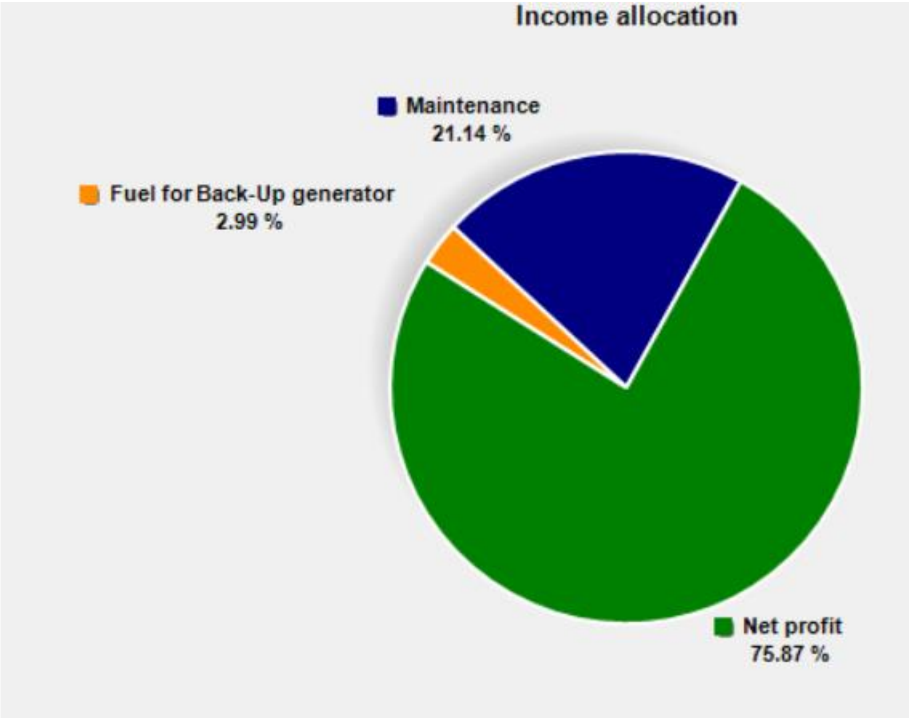


Figure 0-3: income allocation

5.3.6 System summary

This System Summary provides a concise overview of the key financial and performance metrics for the KARONGI-MURUNDI telecom tower off-grid PV system:

Table 17: System Summary

Parameter	Value
Total Installation Cost	58,551.00 USD
Operating Costs	9,234.02 USD/year
Excess Energy (Battery Full)	0.0 MWh/year
Used Solar Energy	58.0 MWh/year
Used Energy Cost	0.200 USD/kWh

4.2.7 Systems Comparison PV and diesel generator

Parameter	PV System	Diesel Generator
Energy Cost (LCOE)	\$0.16/kWh	\$0.925/kWh
Coverage of Energy Demand	78.08%	100% (but fuel-dependent)
Payback Period	2 years	No payback, ongoing costs
Fuel Cost (5 years)	\$0 (solar energy)	132.6 million RWF
CO_2 Emissions	Very low	High
Operational Costs	\$9,234/year	High (fuel & maintenance)
Reliability	High with battery backup	High but fuel-dependent
Return on Investment (ROI)	1139.50%	No significant returns

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

The Karongi-Murundi telecom tower off-grid photovoltaic system represents a significant advancement in sustainable energy infrastructure for remote telecommunications in Rwanda. This concluding analysis synthesizes the system's performance metrics and economic outcomes while proposing future research directions.

6.1. Conclusions

The empirical evidence demonstrates the system's remarkable technical efficacy, achieving a performance ratio of 74.78% and a solar fraction of 78.08%. These metrics validate the engineering decisions regarding module orientation and energy storage capacity. Despite inevitable efficiency losses from environmental factors such as temperature fluctuations and soiling, the system maintains reliable operation throughout varied meteorological conditions. This resilience substantiates the viability of solar technology for mission-critical telecommunications infrastructure in sub-Saharan Africa.

From an economic perspective, the system presents a compelling investment case with a levelized cost of energy at $0.16/kWh—substantially below traditional diesel generation costs in remote locations. The initial capital expenditure of $58,551 yields extraordinary financial returns, evidenced by the abbreviated two-year payback period and remarkable return on investment of 1139.5%. These economic indicators suggest that similar implementations could transform the financial paradigm for off-grid telecommunications power systems across developing regions.

The energy balance analysis reveals a well-calibrated system design that harmonizes generation capabilities with operational requirements. The lithium-ion battery array provides critical autonomy during non-generating periods, while the modest reliance on backup generation (12,711 kWh annually) reflects an appropriate balance between renewable integration and system reliability. This balance is particularly noteworthy given the 159-kWh daily demand profile of the facility.

Beyond technical and economic considerations, the project yields substantial positive externalities through environmental impact reduction and social development. By significantly decreasing carbon emissions from telecommunications operations, the project aligns with Rwanda's national climate commitments while simultaneously enhancing rural connectivity, creating skilled employment opportunities, and demonstrating the feasibility of leapfrog technologies in developing economies.

6.2. Recommendations

Further research should explore next-generation energy storage technologies, including solid-state and flow battery systems, with particular emphasis on optimizing charge/discharge algorithms and predictive maintenance protocols to extend operational lifespans in challenging climatic conditions.

The integration of complementary renewable resources, particularly wind energy, warrants rigorous investigation for hybrid system development. Such configurations could potentially enhance system resilience during extended periods of solar resource variability and further reduce fossil fuel dependencies.

Policy research is essential to identify effective incentive structures and regulatory frameworks that could accelerate similar deployments. Comparative analysis of various financial mechanisms—including tax incentives, capital subsidies, and innovative financing structures—would provide valuable insights for policymakers and investors alike.

Advanced demand-side management strategies represent another promising research direction. Artificial intelligence applications for predictive load forecasting and dynamic consumption optimization could substantially improve system efficiency and reliability while potentially reducing storage requirements.

Finally, comprehensive studies examining the scalability and replicability of this model across diverse geographical and operational contexts would contribute significantly to the broader implementation of sustainable telecommunications infrastructure throughout developing regions.

The Karongi-Murundi implementation thus serves not only as an operational success but also as a foundation for future research and development in sustainable energy systems for telecommunications infrastructure in emerging economies.

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APPENDIX

1. PV module data sheet

PV module - CWT670 - 132PM12 - V

Manufacturer	CW Enerji	**Commercial data**	
Model	CWT670 - 132PM12 - V	Availability :	Prod. Since 2022
		Data source :	Manufacturer 2022
Pnom STC power (manufacturer)	670 Wp	Technology	Si-mono
Module size (W x L)	1.303 x 2.384 m²	Rough module area (Amodule)	3.11 m²
Number of cells	2 x 66	Sensitive area (cells) (Acells)	2.91 m²

Specifications for the model (manufacturer or measurement data)

Reference temperature (TRef)	25 °C	Reference irradiance (GRef)	1000 W/m²
Open circuit voltage (Voc)	46.0 V	Short-circuit current (Isc)	18.51 A
Max. power point voltage (Vmpp)	38.3 V	Max. power point current (Impp)	17.49 A
=> maximum power (Pmpp)	670.0 W	Isc temperature coefficient (muIsc)	7.4 mA/°C

One-diode model parameters

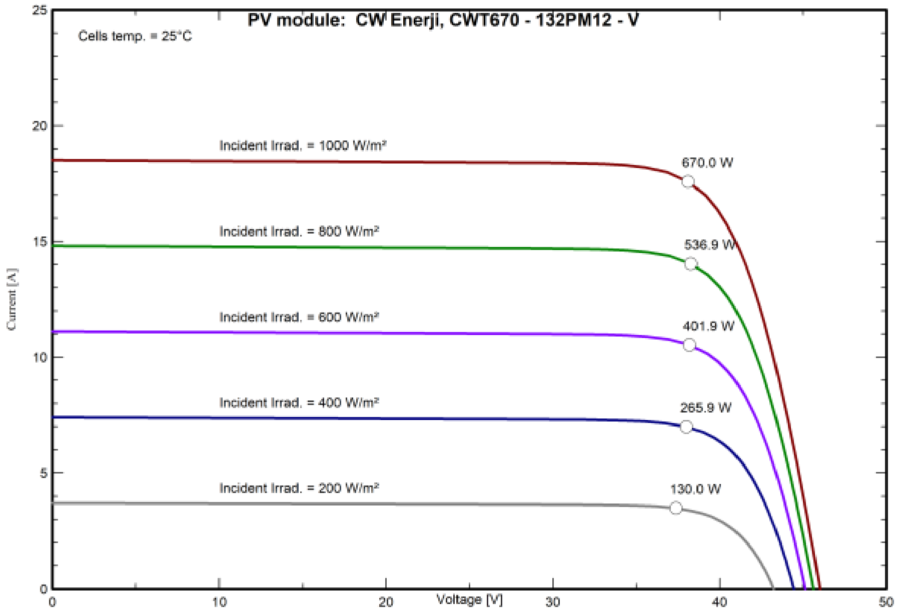
Shunt resistance (Rshunt)	260 Ω	Diode saturation current (IoRef)	0.029 nA
Serie resistance (Rserie)	0.15 Ω	Voc temp. coefficient (MuVoc)	-128 mV/°C
Specified Pmax temper. coeff. (muPMaxR)	-0.34 %/°C	Diode quality factor (Gamma)	1.00
		Diode factor temper. coeff. (muGamma)	0.000 1/°C

Reverse Bias Parameters, for use in behaviour of PV arrays under partial shadings or mismatch

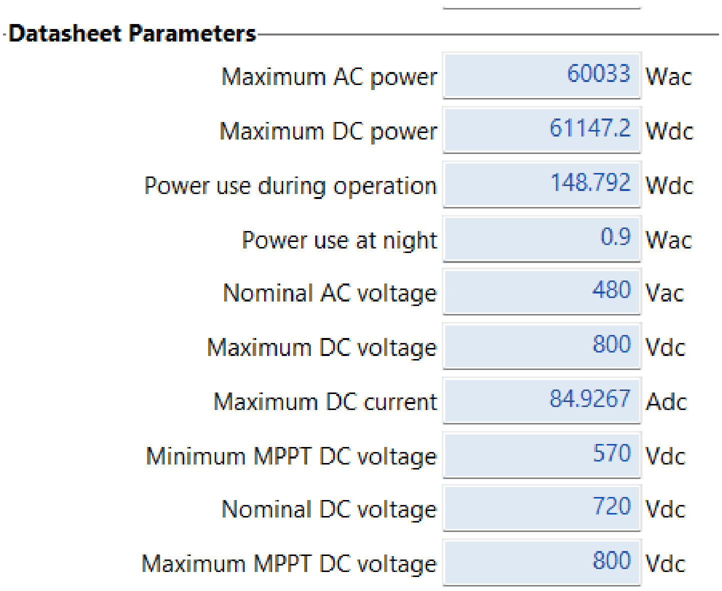
Reverse characteristics (dark) (BRev)	3.20 mA/V²	(quadratic factor (per cell))	
Number of by-pass diodes per module	3	Direct voltage of by-pass diodes	-0.7 V

Model results for standard conditions (STC: T=25 °C, G=1000 W/m², AM=1.5)

Max. power point voltage (Vmpp)	38.1 V	Max. power point current (Impp)	17.60 A
Maximum power (Pmpp)	670.0 Wp	Power temper. coefficient (muPmpp)	-0.34 %/°C
Efficiency(/ Module area) (Eff_mod)	21.6 %	Fill factor (FF)	0.787
Efficiency(/ Cells area) (Eff_cells)	23.0 %		



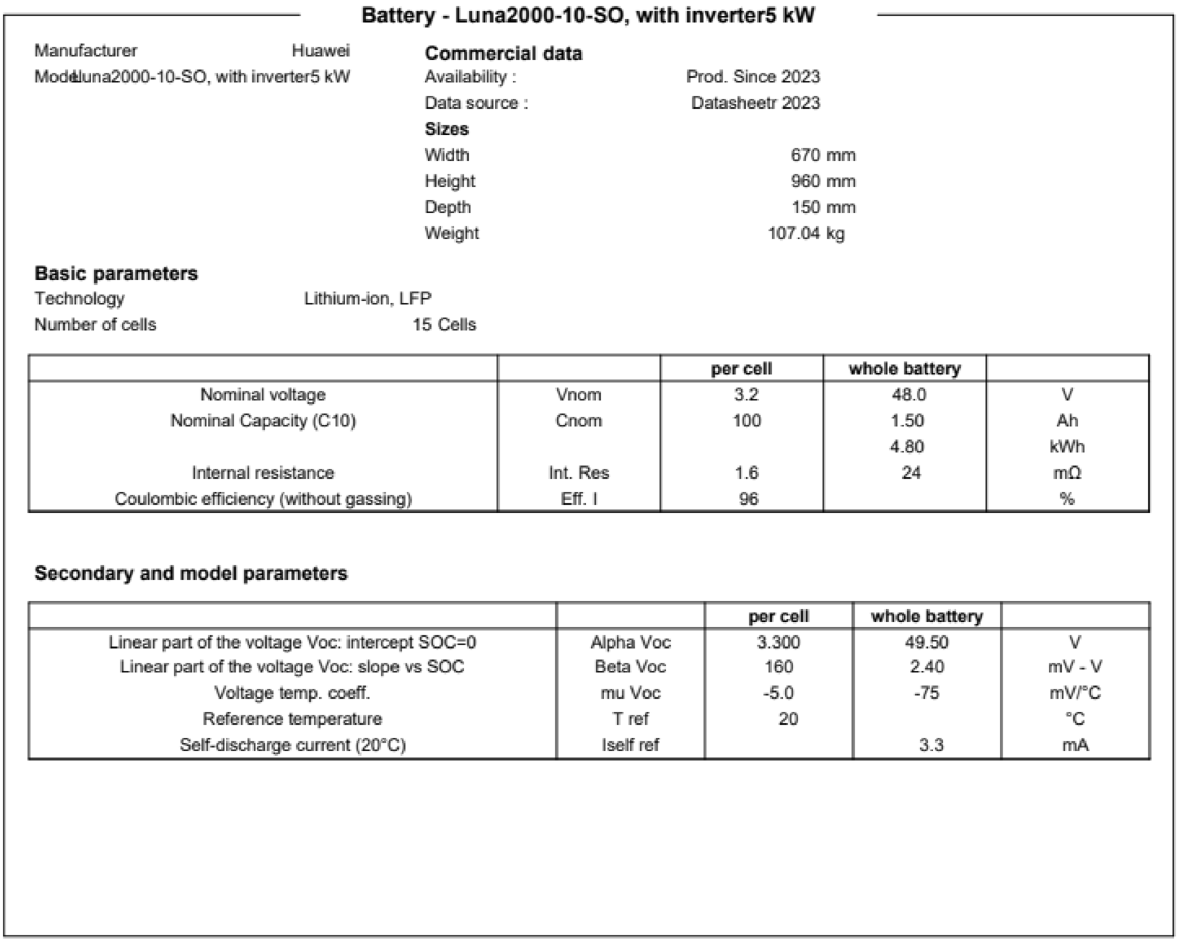
2. Inverter data sheet



Datasheet Parameters

Maximum AC power	60033	Wac
Maximum DC power	61147.2	Wdc
Power use during operation	148.792	Wdc
Power use at night	0.9	Wac
Nominal AC voltage	480	Vac
Maximum DC voltage	800	Vdc
Maximum DC current	84.9267	Adc
Minimum MPPT DC voltage	570	Vdc
Nominal DC voltage	720	Vdc
Maximum MPPT DC voltage	800	Vdc

3. Battery data sheet



Battery - Luna2000-10-SO, with inverter5 kW

Manufacturer	Huawei
Model	Luna2000-10-SO, with inverter5 kW

Commercial data

Availability :	Prod. Since 2023
Data source :	Datasheetr 2023

Sizes

Width	670 mm
Height	960 mm
Depth	150 mm
Weight	107.04 kg

Basic parameters

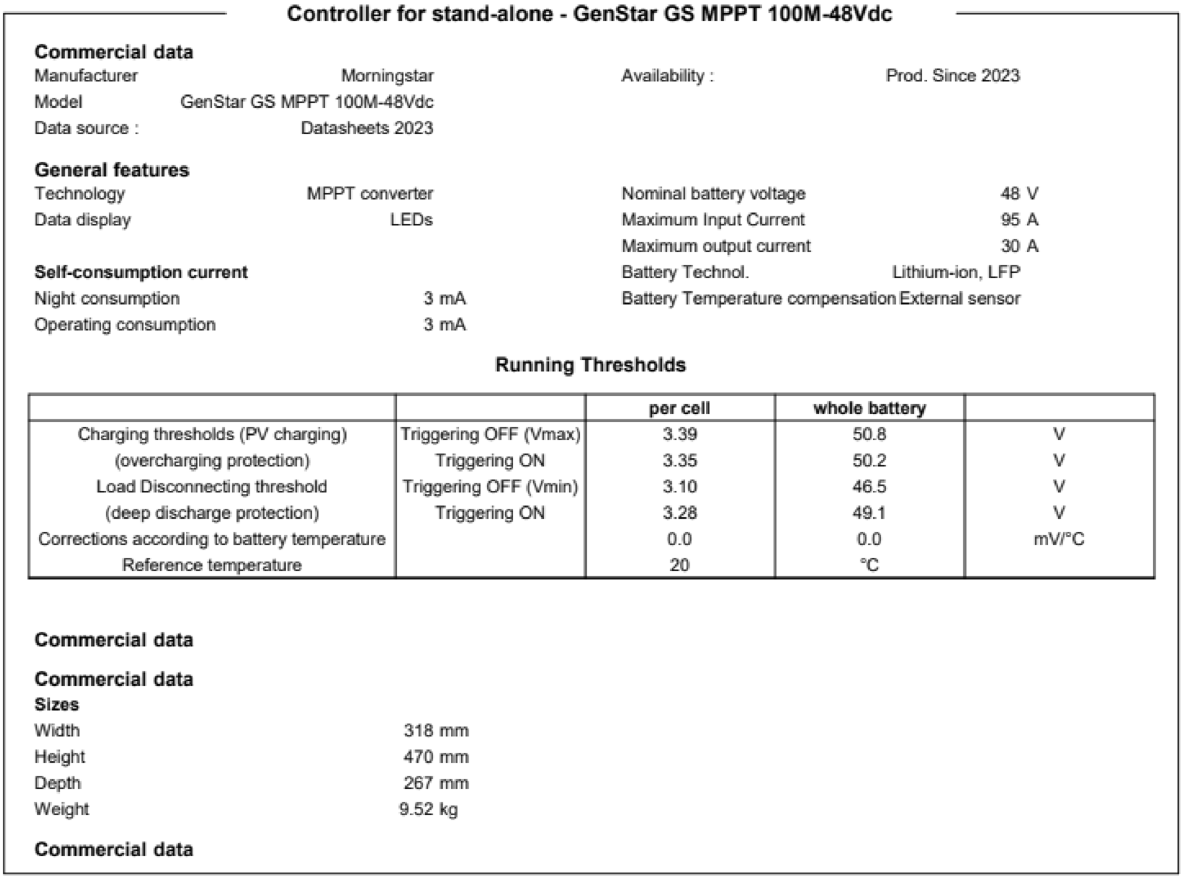
Technology	Lithium-ion, LFP
Number of cells	15 Cells

		per cell	whole battery	
Nominal voltage	Vnom	3.2	48.0	V
Nominal Capacity (C10)	Cnom	100	1.50	Ah
			4.80	kWh
Internal resistance	Int. Res	1.6	24	mΩ
Coulombic efficiency (without gassing)	Eff. I	96		%

Secondary and model parameters

		per cell	whole battery	
Linear part of the voltage Voc: intercept SOC=0	Alpha Voc	3.300	49.50	V
Linear part of the voltage Voc: slope vs SOC	Beta Voc	160	2.40	mV - V
Voltage temp. coeff.	mu Voc	-5.0	-75	mV/°C
Reference temperature	T ref	20		°C
Self-discharge current (20°C)	Iself ref		3.3	mA

4. Controller data sheet



Controller for stand-alone - GenStar GS MPPT 100M-48Vdc

Commercial data

Manufacturer	Morningstar	Availability :	Prod. Since 2023
Model	GenStar GS MPPT 100M-48Vdc		
Data source :	Datasheets 2023		

General features

Technology	MPPT converter	Nominal battery voltage	48 V
Data display	LEDs	Maximum Input Current	95 A
		Maximum output current	30 A
Self-consumption current		Battery Technol.	Lithium-ion, LFP
Night consumption	3 mA	Battery Temperature compensation	External sensor
Operating consumption	3 mA		

Running Thresholds

		per cell	whole battery	
Charging thresholds (PV charging)	Triggering OFF (Vmax)	3.39	50.8	V
(overcharging protection)	Triggering ON	3.35	50.2	V
Load Disconnecting threshold	Triggering OFF (Vmin)	3.10	46.5	V
(deep discharge protection)	Triggering ON	3.28	49.1	V
Corrections according to battery temperature		0.0	0.0	mV/°C
Reference temperature		20	°C	

Commercial data

Commercial data

Sizes

Width	318 mm
Height	470 mm
Depth	267 mm
Weight	9.52 kg

Commercial data